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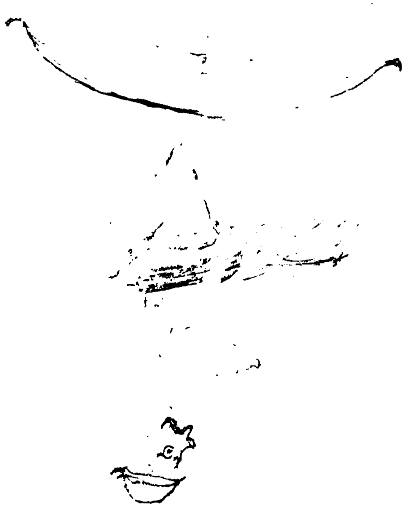

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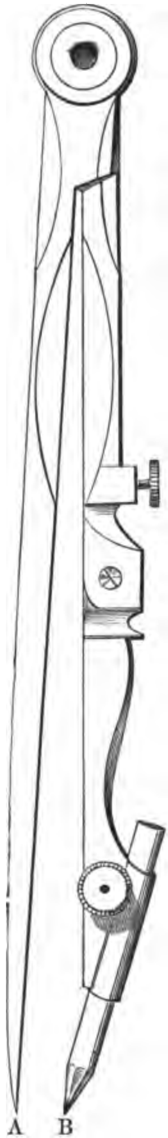

Fig. 1

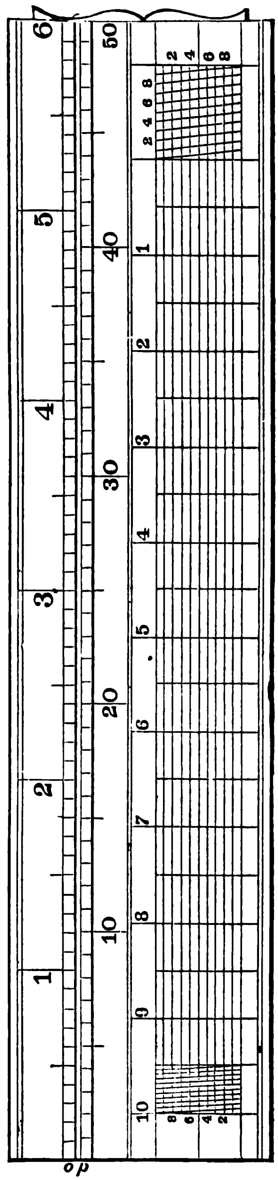

Fig. 2.

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PREFACE.

THIS treatise on the *Special* or *Elementary Geometry* consists of four parts.

PART I. is designed as an introduction. In it the student is made familiar with the geometrical concepts, and with the fundamental definitions and facts of the science. The definitions here given, are given once for all. It is thought that the pupil can obtain his first conception of a geometrical fact, as well, at least, from a correct, scientific statement of it, as from some crude, colloquial form, the language of which he will be obliged to replace by better, after the former shall have become so firmly fixed in his mind, as not to be easily eradicated. No attempt at demonstration is made in this part, although most of the fundamental facts of Elementary Plane Geometry are here presented, and amply and familiarly illustrated. This course has been taken in obedience to the canon of the teacher's art, which prescribes "facts before theories." Moreover, such has been the historic order of development of this, and most other sciences; viz., the *facts* have been known, or conjectured, long before men have been able to give any logical account of them. And does not this indicate what *may* be the natural order in which the individual mind will receive science? When the student has become familiar with the things (concepts) about which his mind is to be occupied, and knows some of the more important of their properties and relations, he is better prepared to reason upon them.

PART II. contains all the essential propositions in Plane, Solid, and Spherical Geometry, which are found in our common text-books, with their demonstrations. The subject of triedrals and the doctrine of the sphere are treated with more than the ordinary fullness. The earlier sections of this part are made short, each treating of a single subject, and the propositions are made to stand out prominently. At the close of each section are *Exercises* designed to illustrate and apply the principles contained in the section, rather than to extend the pupil's knowledge of geometrical facts. These features, together with the synopses at the close of the sections, practical teachers cannot fail to appreciate.

PART III., which is contained only in the *University Edition*, h

been written with special reference to the needs of students in the *University of Michigan*. Our admirable system of public High-Schools, of which schools there is now one in almost every considerable village, promises ere long to become to us something near what the German Gymnasia are to their Universities. In order to promote the legitimate development of these schools, it is necessary that the University resign to them the work of instruction in the elements of the various branches, as fast and as far as they are prepared in sufficient numbers to undertake it. It is thought that these schools should now give the instruction in Elementary Geometry, which has hitherto been given in our ordinary college course. The first two parts of this volume furnish this amount of instruction, and students are expected to pass examination upon it on their entrance into the University. This amount of preparation enables students to extend their knowledge of Geometry, during the Freshman year in the University, considerably beyond what has hitherto been practicable. As a text-book for such students, *Part* III. has been written. At this stage of his progress, the student is prepared to learn to investigate for himself. Hence he is here furnished with a large collection of well classified theorems and problems, which afford a review of all that has gone before, extend his knowledge of geometrical truth, and give him the needed discipline in original demonstration. To develop the power of independent thought, is the most difficult, while it is the most important part of the teacher's work. Great pains have therefore been taken, in this part of the work, to render such aid, and *only such*, as a student ought to require in advancing from the stage in which he has been following the processes of others, to that of independent reasoning. In the second place, this part contains what is usually styled *Applications of Algebra to Geometry*, with an extended and carefully selected range of examples in this important subject. A third purpose has been to present in this part an introduction to what is often spoken of as the *Modern Geometry*, by which is meant the results of modern thought in developing geometrical truth upon the direct method. While, as a system of geometrical reasoning, this Geometry is not philosophically different from that with which the student of Euclid is familiar, and which is properly distinguished as the *special* or *direct* method, the character of the facts developed is quite novel. So much so, indeed, that the student who has no knowledge of Geometry but that which our common text-books furnish, knows absolutely nothing of the domain into which most of the brilliant advances of

the present century have been made. He knows not even the terms in which the ideas of such writers as PONCELET, CHASLES, and SALMON, are expressed, and he is quite as much a stranger to the thought. In this part are presented the fundamental ideas concerning *Loci*, *Symmetry*, *Maxima* and *Minima*, *Isoperimetry*, the theory of *Transversals*, *Anharmonic Ratio*, *Polars*, *Radical Axes*, and other modern views concerning the circle.

PART IV. is *Plane* and *Spherical Trigonometry*, with the requisite Tables. While this Part, as a whole, is much more complete than the treatises in common use in our schools, it is so arranged that a shorter course can be taken by such as desire it. Thus, for a shorter course in Plane Trigonometry, see NOTE on page 55. In Spherical Trigonometry, the first three sections, either with or without the *Introduction* on Projection, will afford a very satisfactory elementary course.

A few words as to the manner in which this plan has been executed, may be important. In general, the *Definitions* are those usually given, with such slight alterations as have been suggested by reflection and experience. There are, however, a few exceptions. Among these is the definition of an *Angle*. I can but regard the attempt to define an angle as *The difference in direction between two lines*, or *The amount of divergence*, as needlessly vague, abstract, and perplexing to a student, as well as questionable on philosophical grounds. The definition given in the text will be seen to be, at bottom, the old one, the conception being slightly altered to bring it into more close connection with common thought, and also with the idea of an angle as generated by the revolution of a line. As to *Parallels*, and the definition of *similarity*, my experience as a teacher is decidedly in favor of retaining the old notions. So also in adopting a definition of a *Trigonometrical Function*, I am compelled to adhere to the geometrical conception. A ratio is a complex concept, and consequently not so easy of application as a simple one. For this reason, among others, I prefer the *differential* to the *differential coefficient*, in the calculus, and a *line* to a *ratio*, in Trigonometry. Moreover, I have found that students invariably rely upon the geometrical conception, even when first taught the other; hence I am not surprised that all our writers who define a trigonometrical function as a ratio, hasten to tell the pupil what it means, by giving him the geometrical illustrations. Nor are the superior facility which the geometrical conception affords for a full elucidation of the doctrine of the signs of the functions, and its admirable adaptation to fix these laws in the mind, considerations to be lost sight of in selecting the definition.

Surely no apology is needed, at the present day, for introducing the idea of *motion* into Elementary Geometry, notwithstanding the rigorous and disdainful manner with which its entrance was long resisted by the old Geometers. And, having admitted this idea, the conception of loci as generated by motion would seem to follow as a logical necessity. In like manner, I take it, the *Infinitesimal* method must come in. Its directness, simplicity, and necessity in applied mathematics, demand its recognition in the elements. In two or three instances, I have presented the *reductio ad absurdum*, where the methods are equivalents, and have always in presenting the infinitesimal method woven in the idea of *limits*, which I conceive to be fundamentally the same as the infinitesimal. Thus we bring the lower and higher mathematics into closer connection.

The *order of arrangement* in *Plane Geometry* (Chap. I.), is thought to be simple, philosophical, and practical. A glance at the table of contents will show what it is. This arrangement secures the very important result, that each section presents some particular *method of proof*, and holds the student to it, until it is familiar. True, it requires that a larger number of propositions be demonstrated from fundamental truths; but who will consider this an objection?

To such as consider it the sole province of geometrical demonstration, to convince the mind of the truth of a proposition, not a few theorems in these and ordinary pages must seem quite superfluous. To them, *Prop.* I., page 121, may afford some merriment. But those who, with myself, consider Geometry as a branch of practical logic, the aim of which is to detect and state the steps which actually lie between premise and conclusion, will see the propriety of such demonstrations; and for each individual of the other class, a separate treatise will be needed, since no two minds will intuitively grant exactly the same propositions.

To Ex-President HILL, of Harvard, I am indebted for the confirmation of an opinion which had been previously forming in my mind, that the study of Geometry as a branch of logic, should be preceded by a presentation of its leading facts. The works of COMPAGNON, TAPPAN, and our lamented countryman, CHAUVENET, have been within reach during the entire work of preparation, and this volume would have been different, in some respects, if any one of these able treatises had not appeared before it.

In the preparation of PART III. the works of ROUCHÉ et COMBEROUSSE and MULCAHY have been freely used. For the very concise elegant form in which the principle of Delambre, for the pre-

cise calculations of Trigonometrical Functions near their limits, is embodied in TABLE III., I am indebted to the recent work of President ELI T. TAPPAN, of Kenyon College, Ohio.

My long and intimate intercourse with Professor G. B. MERRIMAN, now of the department of Physics in the University, has been a source of great profit to me in the preparation of the entire work. His sound, practical judgment as a teacher of Geometry, and cultivated taste and skill as a Mathematician, have been ever at my service, and have done more than I can tell, in giving form to the work, both as respects its matter and its spirit.

EDWARD OLNEY.

UNIVERSITY OF MICHIGAN,
ANN ARBOR, *January*, 1872.

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CHAPTER I.

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CHAPTER II.

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SPECIAL OR ELEMENTARY

GEOMETRY.

INTRODUCTION.

SECTION I.

LOGICO-MATHEMATICAL TERMS.*

1. ***A Proposition*** is a statement of something to be considered or done.

ILL.—Thus, the common statement, "Life is short," is a proposition; so, also, we make, or state a proposition, when we say, "Let us seek earnestly after truth."—"The product of the divisor and quotient, plus the remainder, equals the dividend," and the requirement, "To reduce a fraction to its lowest terms," are examples of Arithmetical propositions.

2. Propositions are distinguished as *Axioms, Theorems, Lemmas, Corollaries, Postulates,* and *Problems.*

3. ***An Axiom*** is a proposition which states a principle that is so simple, elementary, and evident as to require no proof.

ILL.—Thus, "A part of a thing is less than the whole of it," "Equimultiples of equals are equal," are examples of axioms. If any one does not admit the truth of axioms, when he understands the terms used, we say that his mind is not sound, and that we cannot reason with him.

4. ***A Theorem*** is a proposition which states a real or supposed fact, whose truth or falsity we are to determine by reasoning.

ILL.—"If the same quantity be added to both numerator and denominator of a proper fraction, the value of the fraction will be increased," is a *theorem.* It is a statement the truth or falsity of which we are to determine by a course of reasoning.

---

* That is, terms used in the science in consequence of its logical character. The science of the Pure Mathematics may be considered as a department of practical logic.

5. *A Demonstration* is the course of reasoning by means of which the truth or falsity of a theorem is made to appear. The term is also applied to a logical statement of the reasons for the processes of a rule. A solution tells *how* a thing is done: a demonstration tells *why* it is so done. A demonstration is often called *proof*.

6. *A Lemma* is a theorem demonstrated for the purpose of using it in the demonstration of another theorem.

ILL.—Thus, in order to demonstrate the rule for finding the greatest common divisor of two or more numbers, it may be best first to prove that "A divisor of two numbers is a divisor of their sum, and also of their difference." This theorem, when proved for such a purpose, is called a *Lemma*.

The term *Lemma* is not much used, and is not very important, since most theorems, once proved, become in turn auxiliary to the proof of others, and hence might be called lemmas.

7. *A Corollary* is a subordinate theorem which is suggested, or the truth of which is made evident, in the course of the demonstration of a more general theorem, or which is a direct inference from a proposition.

ILL.—Thus, by the discussion of the ordinary process of performing subtraction in Arithmetic, the following *Corollary* might be suggested: "Subtraction may also be performed by addition, as we can readily observe what number must be added to the subtrahend to produce the minuend."

8. *A Postulate* is a proposition which states that something can be done, and which is so evidently true as to require no process of reasoning to show that it is possible to be done. We may or may not know how to perform the operation.

ILL.—Quantities of the same kind can be added together.

9. *A Problem* is a proposition to do some specified thing, and is stated with reference to developing the method of doing it.

ILL.—A problem is often stated as an incomplete sentence, as, "To reduce fractions to a common denominator."—This incomplete statement means that "We propose to show how to reduce fractions to a common denominator." Again, the problem "To construct a square," means that "We propose to draw a figure which is called a square, and to tell how it is done."

10. *A Rule* is a formal statement of the method of solving a general problem, and is designed for practical application in solving special examples of the same class. Of course a rule requires a demonstration.

11. A Solution is the process of performing a problem or an example. It should usually be accompanied by a demonstration of the process.

12. A Scholium is a remark made at the close of a discussion, and designed to call attention to some particular feature or features of it.

ILL.—Thus, after having discussed the subject of multiplication and division in Arithmetic, the remark that "Division is the converse of multiplication," is a scholium.

SYNOPSIS.

Subject of the section.
Proposition. *Ill.*
Varieties of propositions.
Axiom. *Ill.*
One who will not admit the truth of axioms.
Theorem. *Ill.*
Demonstration. Difference between a solution and a demonstration.
Lemma. *Ill.* Why the term is unimportant.
Corollary. *Ill.*
Postulate. *Ill.*
Problem. How stated. *Ill.*
Rule.
Solution.
Scholium. *Ill.*

SECTION II.

THE GEOMETRICAL CONCEPTS.*

POINTS.

13. A Point is a place without size. Points are designated by letters.

ILL.—If we wish to designate any particular point (place) on the paper, we put a letter by it, and sometimes a dot on it. Thus, in *Fig.* 8, the ends of the line, which are points, are designated as "point A," "point D;" or, simply, as A and D. The points marked on the line are designated as "point B," "point C," or as B and C. F and E are two points above the line.

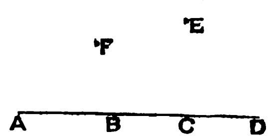

FIG. 8.

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* A concept is a thing thought about;—a thought-object. Thus, in Arithmetic, number is the concept; in Botany, plants; in Geometry, as will appear in this section, points, lines, and solids. These may also be said to constitute the *subject-matter* of the science.

LINES.

14. ***A Line*** is the path of a point in motion. Lines are represented upon paper by marks made with a pen or pencil, the point of the pen or pencil representing the moving point. A line is designated by naming the letters written at its extremities, or somewhere upon it.

ILL.—In each case in *Fig.* 4, conceive a point to start from A and move along the path indicated by the mark to B. The path thus traced is a line. *Since a true point has no size, a line has no breadth*, though the marks by which we represent lines have some breadth. The first and third lines in the figure are each designated as "the line AB." The second line is considered as traced by a point starting from A and coming around to A again, so that B and A coincide. This line may be designated as the line A*mn*A, or A*mn*B. In the fourth case, there are three lines represented, which are designated, respectively, as A*m*B, A*n*B, and A*c*B; or, the last, as AB.

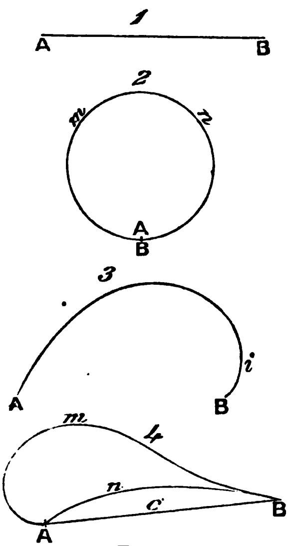

FIG. 4.

15. Lines are of ***Two Kinds***, *Straight* and *Curved*. A straight line is also called a *Right Line*. A curved line is often called simply a *Curve*.

16. ***A Straight Line**** is a line traced by a point which moves constantly in the same direction.

17. ***A Curved Line*** is a line traced by a point which constantly changes its direction of motion.

ILL'S.—Thus in 1, *Fig.* 4, if the line AB is conceived as traced by a point moving from A to B, it is evident that this point moves in the same direction throughout its course; hence AB is a straight line. If a body, as a stone, be let fall, it moves constantly toward the centre of the earth; hence its path represents a straight line. If a weight be suspended by a string, the string represents a straight line. Considering the line represented by A*i*B, *Fig.* 4, as the path of a point moving from A to B, we see that the direction of motion is constantly changing. For example, if this were a line traced on a map, we

* The word "line" used alone signifies "straight line."

would say, that, starting from A, the point begins to move nearly north, but keeps changing its direction more and more toward the east, until at 3 it moves directly east; and from 3 it continues to change its course and moves more and more toward the south, till at *i* it is moving directly south. The same general truth is illustrated in 2 and 4, *Fig.* 4. The path of a ball thrown into the air, in any direction except directly up, represents a curved line. Most of the lines seen in nature are curved, as the edges of leaves, the shore of a river or lake, etc. Sometimes a path like that represented in *Fig.* 5 is called, though improperly, a *Broken Line.* It is not *a* line at all; that is, not *one* line: it is a series of straight lines.

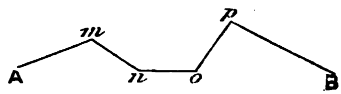

FIG. 5.

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SURFACES.

18. ***A Surface*** is the path of a line in motion.*

19. Surfaces are of ***Two Kinds,*** *Plane* and *Curved.*

20. ***A Plane Surface,*** or simply a *Plane*, is a surface with which a straight line may be made to coincide in any direction. Such a surface may always be conceived as the path of a straight line in motion.

21. ***A Curved Surface*** is a surface in which, if lines are conceived to be drawn in all directions, some or all of them will be curved lines.

ILL'S.—Let AB, *Fig.* 6, be supposed to move to the right, so that its extremities A and B move at the same rate and in the same direction, A tracing the line AD, and B, the line BC. The path of the line, the figure ABCD, is a surface. This page is a surface, and may be conceived as the path of a line sliding like a ruler from top to bottom of it, or from one side to the other. Such a path will have length and breadth, being in the latter respect unlike a line, which has only length.

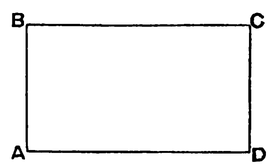

FIG. 6.

As a second illustration, suppose a fine wire bent into the form of the curve A*m*B, *Fig.* 7, and its ends A and B stuck into a rod, XY. Now, taking the rod XY in the fingers and rolling it, it is evident that the path of the line represented by the wire A*m*B, will be the surface of a ball (sphere).

* Should it be said that irregular surfaces are not included in this definition, the sufficient reply is, that such surfaces are not subjects of Geometrical investigation, except approximately, by means of regular surfaces.

Again, suppose the rod XY be placed on the surface of this paper so that the wire AmB shall stand straight up from the paper, just as it would be if we could take hold of the curve at m and raise it right up, letting XY lie as it does in the figure. Now slide the rod straight up or down the page, making both ends move at the same rate. The path of AmB will be like the surface of a half-round rod (a semi-cylinder).

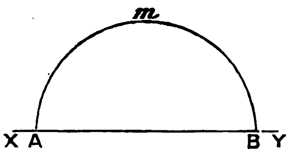

Fig. 7.

Thus we see how surfaces plane and curved may be conceived as the paths of lines in motion.

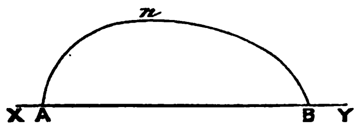

Fig. 8.

Ex. 1. If the curve AnB, *Fig.* 8, be conceived as revolved about the line XY, the surface of what object will its path be like?

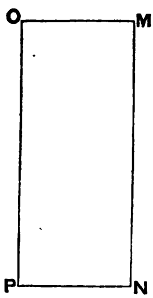

Fig. 9.

Ex. 2. If the figure OMNP, *Fig.* 9, be conceived as revolved about OP, what kind of a path will MN trace? What kind of paths will PN and OM trace?

Ans. One path will be like the surface of a joint of stove-pipe, *i. e.*, a cylindrical surface; and one will be like a flat wheel, *i. e.*, a circle.

Ex. 3. If you fasten one end of a cord at a point in the ceiling and hang a ball on the other end, and then make the ball swing around in a circle, what kind of a surface will the string describe?

[Note.—The student is not necessarily expected to give the geometrical name of the surface, but rather to tell in his own way what it is like, so as to make it clear that he conceives the thing itself.]

Ex. 4. If you were to draw lines in all directions on the surface of the stove-pipe, might any of them be straight? Could *all* of them be straight? What kind of a surface is this, therefore?

Ex. 5. Can you draw a straight line on the surface of a ball? On the surface of an egg? What kind of surfaces are these?

Ex. 6. When the carpenter wishes to make the surface of a board perfectly flat, he takes a ruler whose edge is a straight line, and lays this straight edge on the surface in all directions, watching closely

to see if it always touches. Which of our definitions is he illustrating by his practice?

Ex. 7. When the miller wishes to make flat the surface of one of the large stones with which wheat is ground into flour, he sometimes takes a ruler with a straight edge, and smearing the edge with paint, applies it in all directions to the surface, and then chips off the stone where the paint is left on it. What principles is he illustrating?

Ex. 8. How can you conceive a straight line to move so that it shall not generate a surface?

b.f.l.

ANGLES.

22. ***A Plane Angle,*** or simply an *Angle,* is the opening between two lines which meet each other. The point in which the lines meet is called the ***vertex,*** and the lines are called the ***sides.*** An angle is designated by placing a letter at its vertex, and one at each of its sides. In reading, we name the letter at the vertex when there is but one vertex at the point, and the three letters when there are two or more vertices at the same point. In the latter case, the letter at the vertex is put between the other two.

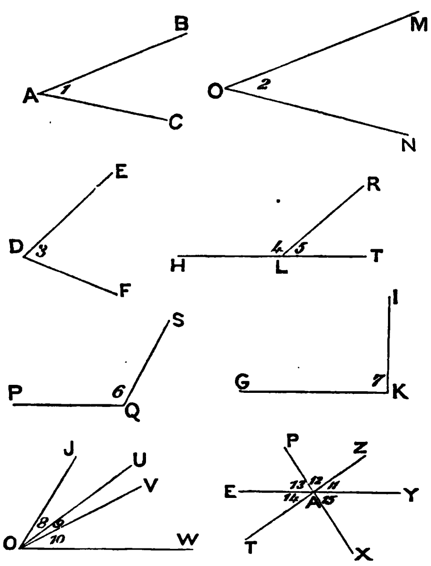

Fig. 10.

ILL.—In common language an angle is called a *corner.* The opening between the two lines AB and AC, in which the figure 1 stands, is called the angle A; or, if we choose, we may call it the angle BAC. At L there are two vertices, so that were we to say the angle L, one would not know whether we meant the angle (corner) in which 4 stands, or that in which 5 stands. To avoid this ambiguity, we say the angle HLR for the former, and RLT for the latter. The angle ZAY is the corner in which 11 stands; that is, the opening between the two lines AY and AZ. In designating an angle by three letters, it is immaterial which letter stands first so that the one at the vertex is put between the other two. Thus, PQS and SQP are both designations of the angle in which 6

stands. An angle is also frequently designated by putting a letter or figure in it and near the vertex.

23. ***The Size of an Angle*** depends upon the rapidity with which its sides separate, and not upon their length.

ILL.—The angles BAC and MON, *Fig.* 10, are equal, since the sides separate at the same rate, although the sides of the latter are more prolonged than those of the former. The sides DF and DE separate faster than AB and AC, hence the angle EDF is greater than the angle BAC.

24. ***Adjacent Angles*** are angles so situated as to have a common vertex and one common side lying between them.

ILL.—In *Fig.* 10, angles 4 and 5 are adjacent, since they have the common vertex L, and the common side LR. Angles 9 and 10 are also adjacent, as are also 8 and 9.

25. Angles are distinguished as *Right Angles* and *Oblique Angles*. Oblique angles are either *Acute* or *Obtuse*.

26. ***A Right Angle*** is an angle included between two straight lines which meet each other in such a manner as to make the adjacent angles equal. ***An Acute Angle*** is an angle which is less than a right angle, *i. e.*, one whose sides separate less rapidly. ***An Obtuse Angle*** is an angle which is greater than a right angle, *i. e.*, one whose sides separate more rapidly.

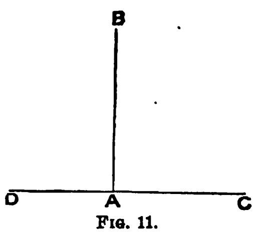

FIG. 11.

ILL.—As in common language an angle is called a *corner*, so a right angle is called a *square corner*; an acute, a *sharp corner*; and an obtuse angle might be called a blunt corner. In *Fig.* 11, BAC and DAB are right angles. In *Fig.* 10, 1, 2, 3, 5, 8, 9, and 10 are acute angles, 4 and 6 are obtuse, and 7 is a right angle.

A SOLID.

27. ***A Solid*** is a limited portion of space. It may also be conceived as the path of a surface in motion.

ILL.—Suppose you have a block of wood like that represented in *Fig.* 12, with all its corners (angles) square corners (right angles). Hold it still in your

fingers a moment, and fix your mind upon it. Now take the block away and think of the space (place) where it was. This space will be of just the same form as the block of wood, and by a little effort you can think of it just as well as of the wood. This *space* is an example of what we call a *Solid* in Geometry. In fact, the solids of Geometry are not solids at all in the common sense of solids; they are only just *places of certain shapes.*

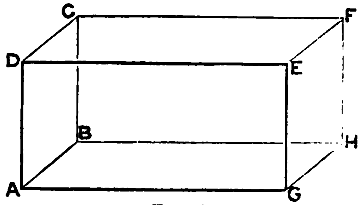

FIG. 12.

Again, hold your ball still a moment in your fingers and then let it drop, and think of the place it filled when you had it in your fingers. It is this *place*, shaped just like your ball, that we think about, and talk about as a *solid*, in Geometry.

In order to see how a solid may be conceived as the path of a surface, suppose you cut out a piece of paper of just the same size as the end of the block represented in Fig. 12. Let ABCD represent this piece of paper. Now, holding the paper in a perpendicular position, as ABCD is represented in the figure, move it along to the right, so that its angles shall trace the lines AG, BH, DE, and CF. When the paper has moved to the position GHFE, its path will be just the same space as the block of wood occupied. This path, or the space through which the surface represented by the piece of paper moved, is the solid.

Ex. 1. If a semicircle is conceived as revolved around its diameter, what is the path through which it moves? See *Fig.* 7.

Ex. 2. If the surface OMNP, *Fig.* 9, is conceived as revolved around OP, what is the path through which it moves?

CAUTION.—The student needs to be careful and distinguish between the *surface* traced by the *line* MN, and the *solid* traced by the *surface* OMNP.

Ex. 3. If the surface represented by ABC be conceived as revolved about its side CA, what kind of a solid is its path?

[NOTE.—As has been said before, the student is not necessarily expected to *name* these solids, but rather to show, in his own language, that he has the conception.]

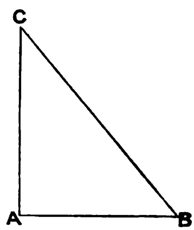

FIG. 13.

Ex. 4. As you fill a vessel with water, what is the solid traced by the surface of the water?

Ans. The same as the space within the vessel.

Ex. 5. If a circle is conceived as lying horizontally, and then moved directly up, what will be the solid described, *i. e.*, its path? Do not confound the surface described with the solid. What describes the surface? What the solid?

EXTENSION AND FORM.

28. Extension means a stretching or reaching out. Hence, a *Point* has no extension. It has only position (place). A *Line* stretches or reaches out, but only in length, as it has no width. Hence, a line is said to have *One Dimension,* viz., length. A *Surface* extends not only in length, but also in breadth; and hence has *Two Dimensions,* viz., length and breadth. A *Solid* has *Three Dimensions,* viz., length, breadth, and thickness.

ILL.—Suppose we think of a point as capable of stretching out (extending) in one direction. It would become a line. Now suppose the line to stretch out (extend) in another direction—to widen. It would become a surface. Finally, suppose the surface capable of thickening, that is, extending in another direction. It would become a solid.

29. The *Limits* (extremities) of a line are points.
The *Limits* (boundaries) of a surface are lines.
The *Limits* (boundaries) of a solid are surfaces.

30. Magnitude (size) is the result of extension. Lines, surfaces, and solids are the geometrical magnitudes. A point is not a magnitude, since it has no size. The magnitude of a line is its length; of a surface, its area; of a solid, its volume.

31. Figure or Form (shape) is the result of position of points. The form of a line (as straight or curved) depends upon the relative position of the points in the line. The form of a surface (as plane or curved) depends upon the relative position of the points in it. The form of a solid depends upon the relative position of the points in its surface. Lines, surfaces, and solids are the geometrical figures.*

ILL.—In *Fig.* 14, it is easy to conceive the form of the lines by knowing the position of points in the lines. By taking a quantity of common pins of different lengths, sticking them upright in a board, and conceiving the heads to represent points in a surface, we can readily see how the position of the points in a surface determine its form.

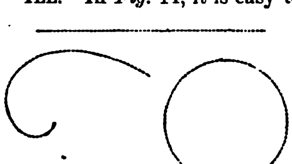

FIG. 14.

Ex. 1. Suppose a line to begin to con-

* Lines, surfaces, and solids are called magnitudes when reference is had to their *extent*, and figures when reference is had to their *form*.

tract in length, and continue the operation till it can contract no longer, what does it become? That is, what is the minor limit of a line?

Ex. 2. If a surface contracts in one dimension, as width, till it reaches its limit, what does it become? If it contracts to its limit in both dimensions, what does it become?

Ex. 3. If a solid contracts to its limit in one dimension, what does it pass into? If in two dimensions? If in three dimensions?

Ex. 4. What kind of a surface is that, every point in which is equally distant from a given point?

32. Geometry treats of *magnitude* and *form* as the result of extension and position.

The *Geometrical Concepts* are points, lines, surfaces (including plane and spherical angles), and solids (including solid angles).

The *Object* of the science is the measurement and comparison of these concepts.

Plane Geometry treats of figures all of whose parts are confined to one plane. *Solid Geometry*, called also *Geometry of Space*, and *Geometry of Three Dimensions*, treats of figures whose parts lie in different planes. The division of Part II. into two chapters is founded upon this distinction. In the *Higher* or *General* Geometry these divisions are marked by the terms "*Of Loci in a Plane*," and "*Of Loci in Space.*"

6d. 16.

SYNOPSIS.

- GEOMETRICAL CONCEPTS.
  - POINT....
    - What.—How designated.—*Ill.*
    - Dimensions of.
    - Limit of Line.—Surface.—Solid.
  - LINE.....
    - What.
    - How designated.
    - Dimensions of.
    - Limit of Surface.
    - Kinds
      - Straight.—What.—*Ill.*
      - Curved.—What.—*Ill.*
      - Broken (?).
  - SURFACE..
    - What.
    - Dimensions of.
    - Limit of Solid.
    - Kinds
      - Plane.—What.—*Ill.*
      - Curved.—What.—*Ill.*
    - Angle
      - What.—Size depends on what.—Adjacent.
      - Kinds
        - Right.—What.—*Ill.*
        - Oblique
          - Acute.—What.—*Ill.*
          - Obtuse.—What.—*Ill.*
  - SOLID.....What.—*Ill.*—Examples.

- GEOMETRY..
  - Treats of
    - Magnitude.—What.—Result of what.
    - Figure or form.—What.—Result of what.
  - Concepts.—What.
  - Object.—What.

PART I.

A FEW OF THE MORE IMPORTANT FACTS OF THE SCIENCE.

SECTION I.

ABOUT STRAIGHT LINES.

33. Prob.*—To measure a straight line with the dividers and scale.*

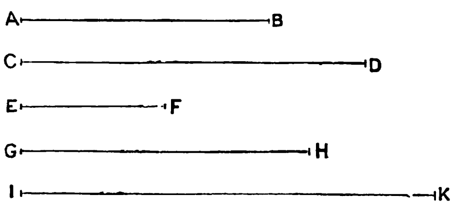

Fig. 15.

Solution.—Let AB, *Fig.* 15, be the line to be measured. Take the dividers, *Fig.* 2 (frontispiece), and placing the sharp point A firmly upon the end A of the line AB, open the dividers till the other point B (the pencil point) just reaches the other end of the line B. Then letting the dividers remain open just this amount, place the point A on the lower end of the left hand scale, as at *o*, *Fig.* 1, and notice where the point B reaches. In this case it reaches 3 spaces beyond the figure 1. Now, as this scale is inches and *tenths* of inches,* the line AB is 1.3 inches long.

Ex. 1. What is the length of CD? *Ans.* .15 of a foot.

Ex. 2. What is the length of EF? *Ans.* .75 of an inch.

Ex. 3. What is the length of GH? *Ans.* $1\frac{1}{2}$ inches.

Ex. 4. What is the length of IK? *Ans.* .18 of a foot.

Ex. 5. Draw a line 3 inches long.

Ex. 6. Draw a line 2.15 inches long.

Ex. 7. Draw a line 1.25 inches long.

Ex. 8. Draw a line .85 of an inch long.

* The next scale to the right is divided into 10ths and 100ths of a foot. Thus from *p* to 10 is 1 tenth of a foot, and the smaller divisions are hundredths.

[NOTE.—Suppose a fine elastic cord were attached by each of its ends to the points A and B of the dividers; when they were opened so as to reach from C to D, *Fig.* 15, the cord would represent the line CD. Now applying the dividers to the scale is the same as laying this cord on the scale. Without the cord, we can imagine the distance between the points of the dividers to be a line of the same length as CD.]

Ex. 9. Find in the same way as above the length and width of this page. Also the distance from one corner (angle) to the opposite one (the diagonal).

---

34. Prob.*—To find the sum of two lines.*

SOLUTION.—To find the sum of AB and CD, I * first draw the indefinite line Ex. With the dividers I obtain the length of AB, by placing one point on A and extending the other to B. This length I now lay off on the indefinite line Ex, by putting one point of the dividers at E and with the other marking the point F. EF is thus made equal to AB.

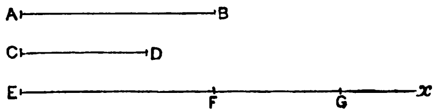

FIG. 16.

In the same manner taking the length of CD with the dividers, I lay it off from F on the line Fx. Thus I obtain EG=EF+FG=AB+CD. Hence, the sum of AB and CD is EG.

[NOTE.—The student may measure EG by (*33*) and find the sum of AB and CD in inches or feet; but it is most important that he be able to look upon EG as the sum itself.]

Ex. 1. Find the sum of AB and EF, *Fig.* 15.

Ex. 2. Find the sum of EF, CD, and GH, *Fig.* 15.

Ex. 3. Make a line twice as long as CD, *Fig.* 16. Three times as long.

---

35. Prob.*—To find the difference of two lines.*

SOLUTION.—To find the difference of AB and CD, I take the length of the less line AB with the dividers; and placing one point of the dividers at one extremity of CD, as C, make Ce = AB. Then is eD the difference of AB and CD, since eD = CD − Ce = CD − AB.

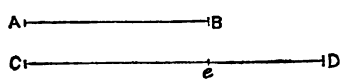

FIG. 17.

Ex. 1. Find the difference of IK and EF, *Fig.* 15.

Ex. 2. Find the difference of GH and CD, *Fig.* 15.

* These elementary solutions are sometimes put in the singular, as the more simple style.

Ex. 3. Find how much longer IK, *Fig.* 15, is than the sum of EF, *Fig.* 15, and CD, *Fig.* 16.

Ex. 4. Find the difference of the sum of AB and CH, and the sum of CD and EF, *Fig.* 15.

---

36. Prob.—*To compare the lengths of two lines; that is, to find their ratio (approximately*).*

SOLUTION.—To compare the lengths of AB and CD, I lay off AB, the shorter, upon CD, as C*a*. (If AB could be applied two or more times to CD, I should apply it as many times as CD would contain it.) Now I apply the remainder of CD, viz., *a*D, to AB, as many times as AB will contain it, which is once with the remainder *b*B. This remainder I now apply to *a*D, and find it contained once with a remainder *c*D. Again, I apply this last remainder to *b*B, and find it contained twice with a remainder *d*B. This last remainder I now apply to *c*D, and find it contained 3 times, without any remainder. This last measure, *d*B, is a common measure of the two lines. Calling *d*B 1, I now observe that

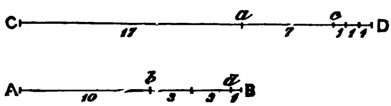

FIG. 18.

$$
\begin{aligned}
dB &= 1;\\
cD &= 3dB = 3;\\
bd &= 2cD = 6;\\
ac &= bB = bd + dB = 7;\\
aD &= ac + cD = 10;\\
AB &= Ab + bB = aD + ac = 17;\\
CD &= Ca + aD = AB + aD = 27.
\end{aligned}
$$

Hence the lines AB and CD are to each other as the numbers 17 and 27; AB is $\frac{17}{27}$ of CD; or, expressed in the form of a proportion, AB : CD : : 17 : 27.

[NOTE.—This process will be seen to be the same as that developed in Arithmetic and Algebra for finding the greatest or highest Common Measure of two numbers, and should be studied in connection with a review of those processes. See COMPLETE ARITHMETIC (*115*), and COMPLETE SCHOOL ALGEBRA (*137*).]

Ex. 1. Find, as above, the approximate ratio of AB to CD, *Fig.* 15.
Ratio, 13 : 18.

Ex. 2. Find, as above, the approximate ratio of CD and IK, *Fig.* 15.
Ratio, 5 : 6.

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* This method does not get the *exact* ratio, because of the imperfection of measurement, and also because lines are sometimes incommensurable, as will appear hereafter.

Ex. 3. Find, as above, the approximate ratio of EF to CH, *Fig.* 15.
Ratio, 1 : 2.

Ex. 4. Find, as above, the approximate ratio of EF to CD, *Fig.* 15.
Ratio, 5 : 12.

---

37. To Intersect is to cross; and a crossing is called an *Intersection.*

38. To Bisect anything is to divide it into two *equal* parts.

39. Prob.—*To bisect a given line.*

SOLUTION.—To bisect the line AB, I take the dividers; and opening them so that the line between their points is more than half as long as AB, I place the sharp point A on the point A, and holding it firmly there, make a little mark with the pencil point B, as nearly as I can guess, opposite the middle of the line. Then, being careful to keep the dividers open just the same, I place the sharp point on B, and make a mark intersecting the first one, as at m. Now, doing just the same on the other side of the line, I make two marks intersecting each other, as at n. Finally, I draw a line from m to n, and where this line crosses AB is its middle point; that is, AO is equal to OB. [Why this is so we do not propose to tell now. The student needs only to learn how to do it. He should *measure* AO and OB, and thus test the accuracy of his work.]

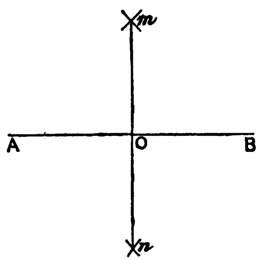

FIG. 19.

Ex. 1. Is it necessary that the dividers be opened just as wide when the marks are made through n, as when they are made through m? Try it.

Ex. 2. Suppose you make the marks through m as directed, but, in making those through n, you have the dividers *wider* open when you put the point on A than when you put it on B; will the line joining m and n then cross AB in the middle? If not, on which side of the middle will O be? Try it.

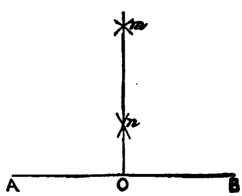

FIG. 20.

Ex. 3. Can you bisect a line by making the marks all on one side of it? If so, do it.

40. *Axiom.—*A straight line is the shortest path between two points.***

ILL.—If a cord is ***stretched*** across the table, it marks a straight line. In this way the carpenter marks a straight line. Having rubbed a cord, called a chalk-line, with chalk, he ***stretches it tightly*** from one point to another on the surfaces upon which he wishes to mark the line, and then raising the middle of the cord, lets it snap upon the surface. So the gardener makes the edges of his paths straight by ***stretching*** a cord along them. These operations depend upon the principle that when the line between the points is the shortest possible, it is straight.

---

41. *Axiom.—Two points in a straight line determine its position.*

ILL.—If the farmer wants a straight fence built, he sets two stakes to mark its ends. From these its entire course becomes known. This is the principle upon which aligning (or sighting) depends. Having given two points in the required line, by looking in the direction of one from the other, we look along a straight line, and are thus able to locate other points in the line. If the points A and B are marked, by putting the eye at A and looking steadily towards B, we can tell whether D and E are in the same straight line with A and B, or not. So we can observe that C′ and C″ are ***not*** in the line; but that C is. This process of discovering other points in a line with two given points is called aligning, or sighting. In this way a row of trees is made straight, or a line of stakes set. It is the principle upon which the surveyor runs his lines, and the hunter aims his gun. In the latter case, the two sights are the given points, and the mark, or game, is a third point, which the marksman wishes to have in the same straight line as the sights.

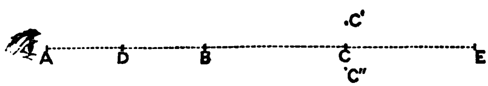

FIG. 21.

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42. *Axiom.—Between the same two points there is one straight line, and only one.*

ILL.—Let any two letters on this page represent the situation of two points; we readily see that there is one, and only one, straight path between them. Again, let a corner of the desk represent one point and a corner of the ceiling of the room represent another point; we perceive at once that, if a point is conceived to pass in a straight line from one to the other, it will always trace

---

* An axiom may be ***illustrated***, but it needs no ***demonstration***. We may explain the terms used and elaborate the condensed statement; but if, when its meaning is clearly understood, any one does not grant the ***truth*** of its statement, he has not a sound mind, and we cannot reason with him.

the same path. In short, as soon as two points are mentioned, we think of the distance between them as a single straight line,—for example, the centre of the earth and the centre of the sun.

Once more, conceive A and B, *Fig.* 21, to be two points in the path of a point moving from A in the direction of B. Now *all* the points in the same direction from A as B is, are in this path; and any point out of this line, as C′ or C″, is in a different direction from A.

In this manner we draw a straight line on paper by laying the straight edge of a ruler on two points through which we wish the line to pass, and passing a pen or pencil along this edge.

COR.—*Two straight lines can intersect in but one point; for, if they had two points common, they would coincide and not intersect.*

Ex. 1. A railroad is to be run from the town A to town B. If it is made straight, through what points will it pass? Can it pass through any points not in the same direction from A as B is?

Ex. 2. If I live on the south side of a straight railroad, and my friend on the north side, but five miles farther east, and two miles farther north, and the road from my house to his is straight, how many times does it cross the railroad?

Ex. 3. Can you always draw a straight line which shall cut a curve (whatever curve it may be) in two points? Try it.

Ex. 4. Detroit is directly east of where I live. How could I drive my horse there and never turn his head to the east? Would he have to travel in straight lines or in a curve? If I drive him on a curve, how can I manage it so that his head will be east for but an instant? If his head is all the time east, what is the line in which I drive him?

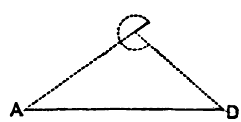

FIG. 22.

SUG.—The figure will suggest how the first may be accomplished.

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43. *A Perpendicular* to a given line is a line which makes a right angle (***26***) with the given line. The latter is also perpendicular to the former. *Oblique Lines* are such as are not perpendicular to each other, and which meet if sufficiently extended.

ILL.—In *Fig.* 11, BA is perpendicular to DC; so also AC is perpendicular to BA. In *Fig.* 10, KG and KI are perpendicular to each other. The other lines in *Fig.* 10 are oblique to each other.

44. Prob.—*To erect a perpendicular to a given line at a given point in the line.*

SOLUTION.—Suppose I want to erect a perpendicular to the line XY, at the point A. With the dividers I measure off a distance AB on one side of the point A, and *an equal distance* AC on the other side. Then opening the dividers a little wider, I put the sharp point on B and make a mark with the pencil point, as at O, about where I think the perpendicular will go. Then, keeping the dividers *open just the same*, I put the sharp point on C, and make a mark intersecting the former one at O. Now, drawing a line through O and A, it is the perpendicular sought.

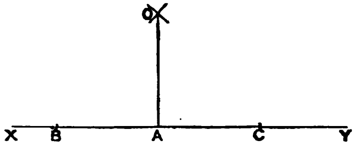

FIG. 23.

Ex. 1. Suppose I make a mistake and close up the dividers a little after making the first mark through O, and then make the second mark; which way will the line lean? Will it be a perpendicular or an oblique line in this case? What kind of an angle would OAY be? What OAX? What kind of angles are these when OA is a perpendicular?

Ex. 2. Suppose I should mistake a point nearer to A than B was taken, and use it as I did C, having the dividers open just alike when I made the two marks through O; which way would the line lean (incline)? (Same questions as in the last.)

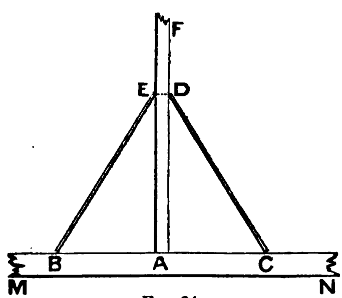

FIG. 24.

ILL.—A carpenter wishes to get the piece of timber AF at right angles to MN, into which it is mortised at A. So he measures off AB and AC, equal distances from A; and taking two poles of equal length (say 10 feet long), has the end of one held steadily at B and the end of the other at C, and moves (racks, as he calls it) the end F to the right or left until the ends E and D of the poles are exactly opposite, as in the figure. AF is then perpendicular to MN.

---

45. Prob.—*From a point without a given line, to draw a perpendicular to the line.*

SOLUTION.—I wish to draw a perpendicular from O to the line XY. I first open the dividers wide enough, so that when I place the sharp point on O the pencil will mark the line XY in two points, as B and C, when it swings around. Marking these two points, I put the sharp point first on B and afterward on C, *keeping them open just* alike in both cases, and make the two marks intersecting at D. Placing the straight edge of the ruler on the points O and D, I draw the line OA along its edge. OA is the perpendicular required.

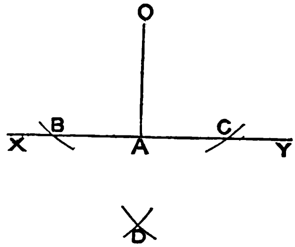

FIG. 25.

Ex. 1. Let fall a perpendicular from a point, as O, upon a straight line, as XY, without making any marks on the opposite side of XY from O.

Ex. 2. A mason wishes to build a wall from O, in the wall AB, "straight across" (perpendicular) to the wall CD, which is 8 feet from AB. He has only his 10-foot pole, which is subdivided into feet and inches, with which to find the point in the opposite wall at which the cross wall must join. How shall he find it?

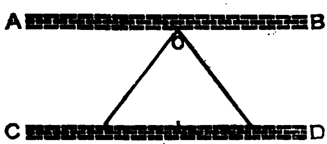

FIG. 26.

SECTION II.

ABOUT CIRCLES.

46. A Circle is a plane surface bounded by a curved line every point in which is equally distant from a point within.

47. The Circumference of a Circle is the curved line every point in which is equally distant from a point within.

48. The Centre of a Circle is the point within, which is equally distant from every point in the circumference.

49. An Arc is a part of a circumference.

50. A Radius is a line drawn from the centre to any point in the circumference of a Circle.

51. A Diameter of a Circle is a line passing through the centre and terminating in the circumference.

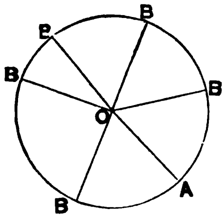

FIG. 27.

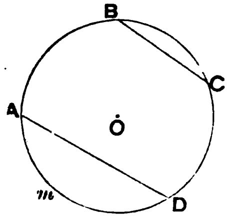

FIG. 28.

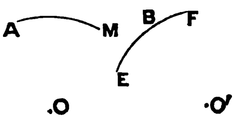

FIG. 29.

ILL.—A circle may be conceived as the path of a line, like OB, *Fig.* 27, one end of which, O, remains at the same point, while the other end, B, moves around it in the plane (say of the paper). OB is the *Radius*, and the path described by the point B is the *Circumference*. AB is a diameter. In *Fig.* 28, the curved line ABCDA (going clear around) is the *Circumference*, O is the *Centre*, and the space within the circumference is the *Circle*. Any part of a circumference as AB, or any of the curved lines BB, *Fig.* 27, is an arc. So also AM and EF, *Fig.* 29, are arcs. EF is an arc drawn from O' as a centre, with the radius O'B.

52. A Chord is a straight line joining any two points in a circumference, but not passing through the centre, as BC or AD, *Fig.* 28. The portion of the circle included between the chord and its arc, as A*m*D, is a SEGMENT.

53. A Tangent to a circle is a straight line which touches the circumference, but does not intersect it, how far soever the line be produced.

54. A Secant is a straight line which intersects the circumference in two points.

EX. 1. Suppose DC, *Fig.* 11, to represent a small wooden rod, and BA a wire stuck into it at right angles. Now if you take the end C of the rod in your fingers and place the end D on the table so that the rod shall stand upright, and then revolve the rod once around like a shaft, what will the wire describe? What the end B? What any point in BA? If you only revolve the rod a little way, what will the point B describe? What does BA represent?

EX. 2. If you take a string, OP, and hold one end at a particular point, O, on your slate or blackboard, while with the other hand you hold the other end, P, of the string upon the end of a pencil or crayon, and then move the end P around O, making a mark as it goes, what will the mark made represent when the pencil or crayon has gone clear

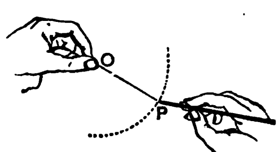

FIG. 30.

around? What will the string represent? What is the surface passed over by the string?

Ex. 3. If you take the dividers, *Fig.* 1, and open them (say 2 inches), and then place the sharp point, A, firmly on the paper while you turn them around, making the pencil point, B, mark the paper as it goes, what kind of a line will be described? What is the line joining the points of the dividers?* What line describes the circle? If the dividers only turn a little way, what is the line described?

Ex. 4. If a boy skating on the ice makes a curve which bends everywhere just alike, what kind of a path will he make? Does the boy describe a circle? How might you conceive the circle inclosed by his path, as described? Is a circle described by a point or by a line?

[NOTE.—The word "circle" is used in common language as equivalent to "circumference." It is also thus used in General Geometry. But, however the words may be used, the pupil should be taught to mark the distinction between the plane surface inclosed and the bounding line.]

Ex. 5. In how many points can a straight line intersect a circumference? In how many points can one circumference intersect another?

Ex. 6. There is a piece of ground in the form of a circle, the radius of which is 100 rods, by which run two roads; one road runs within 80 rods of the centre, and the other within 100 rods. How do the roads lie with reference to the ground?

Ex. 7. When you unwind a thread by drawing it off a spool in the ordinary way, what geometrical line does the unwound thread represent?

Ex. 8. In a circle whose diameter is 50 feet, there are drawn two chords, one is 20 feet long, and the other 30 feet. Which is nearer the centre?

Ex. 9. There are two circles whose radii are respectively 12 and 18 feet. The distance from the centre of one to the centre of the other is 25 feet. Do the circumferences intersect? Would they intersect if the centres were 3 feet apart? How would they lie in reference to each other in the latter case? How if their centres were 30 feet apart? How if they were 35 feet apart?

* The imagination may be aided by supposing a fine elastic cord stretched between the points of the dividers and carried by them.

Ex. 10. What kind of a line is represented by water flying from a swiftly-revolving grindstone?

Ex. 11. If you draw two chords in the same circle, one of which is twice as long as the other, will the arc cut off by the longer chord be twice as long as the arc cut off by the shorter? Will it be more than twice as long, or less?

---

55. Theorem.—*The chord of a sixth part of the circumference of a circle is just equal to the radius of the same circle.*

Ill.—If I draw a circle, and then, being careful not to open or close the dividers, place the sharp point on the circumference at some point, as A, and mark the circumference at another point, as B, with the pencil point, and then move the sharp point to B and mark again, as C, I find that when I have measured off six such chords, each equal to the radius, I return exactly to A, the point of starting.

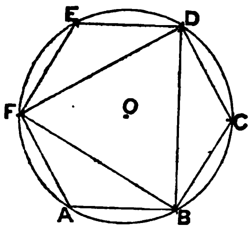

Fig. 31.

Moreover, if I draw the chords AB, BC, etc., I have a regular figure with six equal sides. A figure with six sides is called a hexagon. This hexagon is called *regular*, because its sides are equal each to each, and its angles are also mutually equal.

Again, if I unite the alternate angles of the regular hexagon, as FB, BD, and DF, I have a regular triangle, called an equilateral triangle.

56. Inscribed Figures are figures drawn in a circle, and having the vertices of all their angles in the circumference, as the hexagon and triangle in the last illustration. When the figure is without, and all its sides touch but do not cut the circumference, it is *circumscribed* about the circle.

Ex. 1. Draw a regular hexagon whose side is two inches.

Ex. 2. Inscribe an equilateral triangle in a circle whose radius is one inch.

---

57. Prob.—*To find the centre of a circle when the circumference is drawn* (or, as we usually say, *known*).

Solution.—The circumference of my circle is drawn, but the centre is not

marked. So I want to find the centre. I draw any two chords, as AB and CD (the nearer they are at right angles to each other the better for accuracy). I then bisect each chord with a perpendicular, as AB with the perpendicular MN, and CD with RS (*39*). The intersection of these two perpendiculars, as O, is the centre of the circle. [The pupil must *do* everything with his pencil, ruler, and dividers, just as he says. He must not be of those who "*say* and *do* not." He must do the things told, "over and over," till he can do them neatly and easily.]

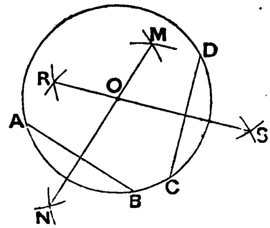

FIG. 32.

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58. Prob.—To pass a circumference through three given points.

SOLUTION.—I wish to pass a circumference through the three given points A, B, and C. [The pupil should first designate three points by dots on his paper, slate, or board, and then proceed according to the solution.] In order to do this, I join A and B with a line, and also B and C. I now bisect these lines with the perpendiculars MN and RS, as in the last problem. The intersection of these perpendiculars, O, is the centre of the required circle. Now setting the sharp point of the dividers upon O and opening them till the pencil point just reaches A (B or C will answer as well), I draw the circumference with O as its centre and the radius OA, and find that it passes through the three given points A, B, and C.

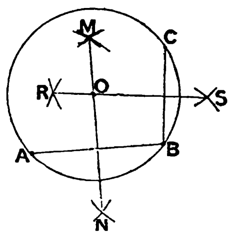

FIG. 33.

Ex. 1. To pass a circumference through the three vertices of a triangle, *i. e.*, to circumscribe a circumference about a triangle, as this operation is technically called.

SUG.—This is just like the last, A, B, and C being the vertices of the triangle. The four figures in the margin represent the successive steps in the solution. First draw the given triangle. Then take the first step in the solution, then the second, etc.

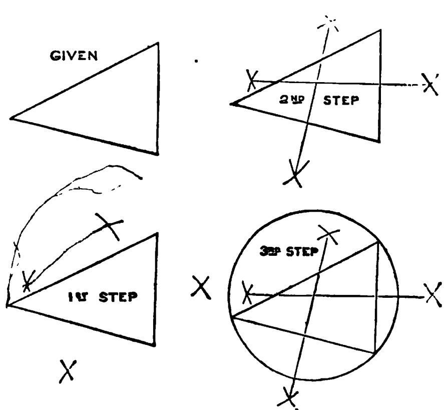

FIG. 24.

Ex. 2. Given the centre of a circle and a point in the circumference, to draw the circle.

SUG.—Make a dot on the board to indicate the centre, and another dot to indicate the point in the circumference to be found. This is what is given. You are

then to draw the circumference, which shall pass through the latter point, and have the former for its centre.

Ex. 3. Draw an arc of a circle, and rub out the mark, if you make any, at the centre, so that you cannot see where the centre is. Then find the centre, and complete the circumference according to these problems.

SUG.—Mark three points in the given arc, and then the example is just like the last. [Do not fail to do it, "over and over," till you can do it quickly and neatly. These exercises require much care in order to get good figures.]

---

59. *Theorem.*—*The circumference of a circle is about* 3.1416 *times its diameter. The Greek letter* π (called p) *is used to represent this number; and hence the circumference is said to be* π *times the diameter.*

ILL.—The pupil can illustrate this fact by taking any wheel which is a true circle, and measuring the diameter with a narrow band of paper (something that will not stretch), and then wrapping this measure about the circumference. He will find that it takes *a little more* than three diameters to go around. Of course he cannot tell exactly how much more. In fact, nobody knows exactly. But the number given above is near enough for most purposes. For many purposes $3\frac{1}{7}$ is sufficiently accurate.

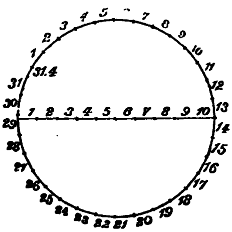

FIG. 35.

By drawing a circle very carefully, say 1 inch in diameter, as in the margin, and dividing the diameter into 10ths inches, a nice pair of dividers can be opened one 10th inch and made to step around the circumference. If it is all done with nicety, it will be found to be a little over 31 steps around, when it is 10 across.

Ex. 1. The distance across a wagon-wheel (the diameter) is 4 feet, how long a bar of iron will it take to make the tire?

Ex. 2. Suppose the crown of your hat is a circular cylinder 7 inches in diameter, how much ribbon will it take for a band, allowing $\frac{1}{4}$ of a yard for the knot?

Ex. 3. How many times will the driving-wheel of an engine, which is 6 feet in diameter, revolve in going from Detroit to Chicago, a distance of 288 miles, allowing nothing for slipping?

Ex. 4. A boy's hoop revolved 200 times in going around a city-square, a distance of 140 rods. What was the diameter of his hoop?

Ex. 5. What is the radius of a circle whose semi-circumference is π? In a circle whose radius is 1, what part of the circumference does $\frac{\pi}{2}$ represent? What part $\frac{\pi}{4}$? What part does 2π represent?

SECTION III.

ABOUT ANGLES.

60. Prob.—*To show how angles are generated and measured.*

Ill.—An angle is generated by a line revolving about one of its extremities. Thus, suppose OB to have started from coincidence with OA, and, O remaining fixed, the line to have revolved to the position OB, the angle BOA would have been generated. When the revolving line has passed one-quarter the way around, as to DO, it has generated a right angle; when one-half way around, as to FO, two right angles; when entirely around, four right angles.

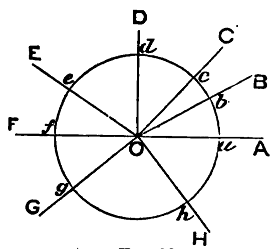

Fig. 36.

Now, if *any circle* be described from O as a centre, *the arc included by the sides of any angle having its vertex at* O, *is the same part of a quarter of this circumference as the angle is of a right angle.* Hence the angle is said to be measured by the arc included by its sides. Thus, the angle COA is measured by the arc *ac*; *i. e.*, it is the same part of a right angle that arc *ac* is of arc *ad*. (See Trigonometry, *3–10*.)

---

61. Theorem.—*The relative lengths of arcs described with the same radius can be found in a manner altogether similar to that given in (36) for comparing straight lines.*

Ill.—If I wish to compare the two arcs *ab* and *cd* described *with the same radii*, I take the dividers, and placing the sharp point on *d* (one end of the shorter arc), open them till the other point is at *c*. I then measure this distance off on *ab* as many times as I can,—in this case 2 times, with a remainder *fb*. This remainder, *fb*, I measure off in the same way upon *dc*, and find it goes *once* with a remainder *gc*. This remainder, *gc*, I apply to the arc *fb*, and find it goes once with a remainder *hb*. This last remainder I find is contained in the last preceding, *gc*, 2 times. Then, counting up the parts, I find that *dc* is made up of 5 parts each equal to *hb*, and *ab* of 13 such parts. Therefore, *ab* is $2\frac{3}{5}$ times as long as *dc*. [The angle O is therefore $2\frac{3}{5}$ times the angle C.]

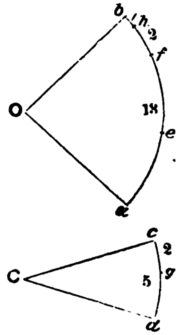

Fig. 37.

Ex. 1. Draw an acute angle and also an obtuse angle, and then compare them as above.

Ex. 2. Draw a small acute angle and a large acute one, and then compare them as above.

Ex. 3. Draw a small acute angle, and then draw another angle 3 times as large.

Ex. 4. Draw an acute angle, and also a right angle, and compare them as above.

SUG.—Article (*39*) shows how to draw a right angle.

Ex. 5. Draw any angle, and then draw another equal to it.

Ex. 6. Show that the angles *a*, *b*, and *c* are respectively $\frac{1}{5}$, $\frac{2}{5}$, and .6 of a right angle.*

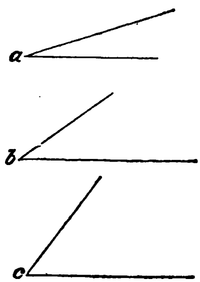

FIG. 38.

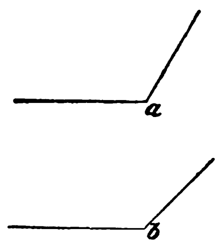

FIG. 39.

Ex. 7. Show that angles *a* and *b*, *Fig.* 39, are respectively $1\frac{1}{3}$ and $1\frac{1}{2}$ times a right angle.

Ex. 8. Draw a regular inscribed hexagon, as in *Fig.* 31, and then comparing any one of its angles with a right angle, find that it is $1\frac{1}{3}$ times a right angle.

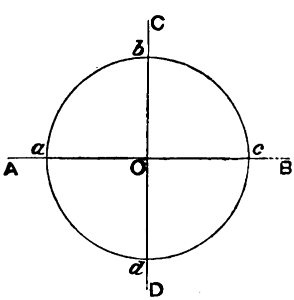

FIG. 40.

Ex. 9. Draw an equilateral triangle, as in *Fig.* 31, and find that any angle of it is $\frac{2}{3}$ of a right angle.

Ex. 10. Show that a right angle is measured by $\frac{1}{4}$ of a circumference.

SOLUTION.—If CD is perpendicular to AB, the four angles formed are equal, and each is a right angle. But, as all of them taken together are measured by the whole circumference, one of them is measured by $\frac{1}{4}$ of the circumference.

* Of course, absolute accuracy is not to be expected in such solutions.

62. *An Inscribed Angle* is an angle whose vertex is in the circumference of a circle, and whose sides are chords, as A, *Fig.* 41.

63. *Theorem.*—*An inscribed angle is measured by one-half the arc included between its sides.*

Ill.—The meaning of **this is that** an inscribed angle like A, which includes any particular arc, as *cd*, is only half as large as an angle would be at the centre, as *c*O*d*, whose sides included the same arc, *cd*, or an equal arc. Thus, in this case, drawing the arc *ab* from A as a centre, with the same radius, O*d*, as *cd* is drawn with, I find that *ab* which measures A is ½ of *cd* which measures *c*O*d*.

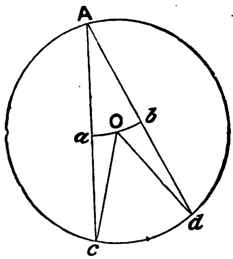

Fig. 41.

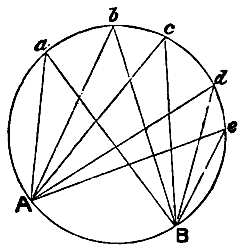

Fig. 42.

Ex. 1. Which of the angles *a, b, c, d, e* is the largest? What is *a* measured by? What *b*? What *c*? What *d*? What *e*? *Fig.* 42.

Ex. 2. Which is the greatest angle, *a, b,* or *c, Fig.* 43? By what is *a* measured? By what *b*? By what *c*? What is the measure of a right angle? [See Example 10 in the preceding set.]

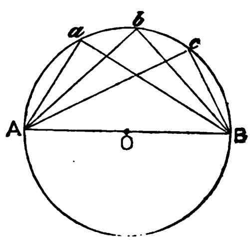

Fig. 43.

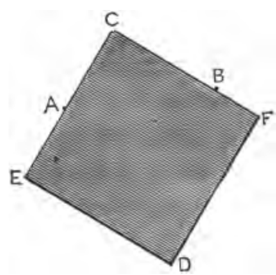

Fig. 44.

Ex. 3. Suppose I take a square card like CEDF, with a hole in one corner as at C, and sticking two pins firmly in my paper, as at A and B, place the corner of the card between them, as in *Fig* 44, and then, keeping the sides of the card snug against the pins, put a

pencil through the hole C and move it around to A and then back to B; what kind of a line will the pencil trace? Will it make any difference whether C is a right angle or not? If any difference, what?

Ex. 4. By what part of a circumference is an angle of a regular inscribed hexagon measured? See (*55*), and *Fig.* 31. How many right angles is the angle of the hexagon equal to? What is the sum of the six angles equal to? *Ans. to last,* 8 right angles.

Ex. 5. Show, from the way in which an equilateral triangle is constructed in *Fig.* 31, that one of its angles is measured by $\frac{1}{6}$ of a circumference, and hence is $\frac{2}{3}$ of a right angle.

---

64. Theorem.— *When two lines intersect, they form either four right angles, or two equal acute and two equal obtuse angles.*

ILL.—[The pupil can illustrate this for himself by drawing lines and noticing what angles are equal.]

Ex. 1. Having a carpenter's square, an instrument represented by MON, I wish to test the angle O and ascertain whether it is, as it should be, a right angle. I draw an indefinite right line AB, and placing the angle O at some point C on this line with ON extending to the right on CB, I draw a line along OM. Turning the square over so that ON shall lie on CA, I draw another line along OM. Three cases may occur.—1st. Suppose the first line drawn along OM is CF, and the second CE; what kind of an angle is O? 2d. Suppose the first line drawn is CE and the second CF; what kind of an angle is O? 3d. Suppose the first and second lines drawn along OM coincide and are CD; what kind of an angle is O?

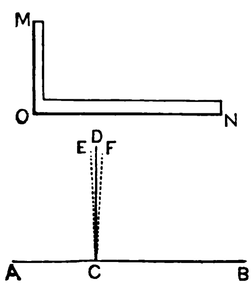

FIG. 45.

Ex. 2. Show that the sum of all the angles formed by drawing lines on one side of a given line, and to the same point in the line, is two right angles.

---

65. Prob.—*To bisect a given angle.*

SOLUTION.—I wish to divide the angle AOB into two equal parts, *i. e.*, to

bisect it. With O, the vertex, as a centre, and any convenient radius, as Oa, I strike an arc, as ba, cutting the sides of the angle. Then from a and b as centres, with the same radius in each case, I strike two arcs intersecting as at P. Drawing a line through P and O, it bisects the angle; *i. e.*, the angle POA = angle BOP. [Let the pupil try this by cutting out the angle AOB, and then folding the paper along the line P, or cutting it through in the line OP, and then putting one angle on the other, and thus see if they do not fit.]

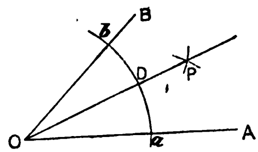

FIG. 46.

Ex. 1. Draw an angle equal to $\frac{1}{2}$ of a right angle.

SUG.—First draw a right angle and then bisect it.

Ex. 2. Draw an angle equal to $\frac{1}{3}$ of a right angle.

SUG.—Draw a circle. Inscribe an equilateral triangle. [Do it neatly, by rule, as in (*55*).] Then bisect any angle of this triangle. This will be $\frac{1}{3}$ of a right angle, since the whole angle is $\frac{2}{3}$. See Ex. 9 (*61*).

Ex. 3. How does it appear that the angle EDF, *Fig.* 31, is $\frac{1}{3}$ of a right angle?

---

66. Parallel Straight Lines are such as, lying in the same plane, will not meet how far soever they are produced either way.

ILL.—The sides of this page are parallel lines, as are also the top and bottom. The lines in *Fig.* 47 are parallel.

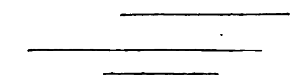
FIG. 47.

67. Prob.—*To draw a line through a given point and parallel to a given line.*

SOLUTION.—I wish to draw a line through the point O and parallel to the line AB. [The pupil should first draw some line, as AB, and mark some point, as O.] I take O as a centre, and with a radius* greater than the shortest distance to AB, as Oa, draw an indefinite arc aP. Then with a as a centre, and *the same* radius, I draw an arc from O to the line AB at b. Taking the distance Ob (the chord) in the dividers, I put the sharp point on a and strike a small arc intersecting this indefinite arc, as at P. Finally, drawing a line through O and P, it is the parallel sought.

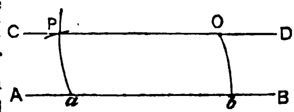

FIG. 48.

* This means "put the sharp point of the dividers on O and open them till the distance between the points (the radius) is more than the distance from O to AB."

***68. Theorem.**—Two parallel lines are everywhere the same distance apart.*

ILL.—Let AB and CD be two parallel lines. I will examine them at the two points O and P. To find how far apart the lines are at these points I draw the perpendiculars OM and PN. [The pupil should not guess at these, but actually draw them as instructed in (44).] Measuring these, I find them equal.

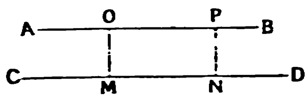

FIG. 49.

We can understand that this proposition must be true, since the lines could not approach each other for awhile and then separate more and more without being crooked; or, if they kept on approaching each other, they would meet after awhile, and so not be parallel.

***69. Theorem.**—Parallel lines make no angle with each other.*

ILL.—Let AB be a straight line, and suppose CD another straight line passing through the point O. Now let CD turn around, first into the position D′C′, then into D″C″, etc., all the time passing through O. It is evident that the angle which this line makes with the line AB is all the time growing less, *i. e.*, $a' < a$, and $a'' < a'$. It is also evident that this angle will become 0 when the lines become parallel; for it becomes less and less all the time, but is always something so long as the lines are not parallel.

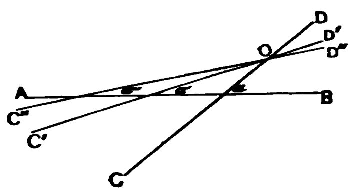

FIG. 50.

***70. Theorem.**—Parallel lines have the same direction with each other.*

ILL.—Thus, in *Fig.* 47, the parallel lines all extend to the right and left, *i. e.*, in the same direction.

Ex. 1. How shall the farmer tell whether the opposite sides of his farm are parallel?

Ex. 2. If we wish to cross over from one parallel road to another, is it of any use to travel farther in the hope that the distance across will be less?

Ex. 3. If a straight line intersects two parallel lines, how many angles are formed? How many angles of the same size? May they *all* be of the same size? When? When will they not be all the same size?

SECTION IV.

ABOUT TRIANGLES.

71. A Plane Triangle, or simply *A Triangle,* is a plane figure bounded by three straight lines.

72. With respect to their sides, triangles are distinguished as *Scalene, Isosceles,* and *Equilateral.* A scalene triangle has no two sides equal. An isosceles triangle has two sides equal. An equilateral triangle has all its sides equal.

73. With respect to their angles, triangles are distinguished as *acute* angled, *right* angled, and *obtuse* angled. An acute angled triangle has three acute angles. A right angled triangle has *one* right angle. An obtuse angled triangle has *one* obtuse angle.

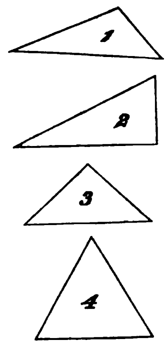

Fig. 51.

Ex. *Fig.* 51 affords illustrations of all the different kinds of triangles. Let the pupil point them out until he is perfectly familiar with the terms. He should also practise drawing the different kinds of triangles, for the purpose of familiarizing the names applied to the different kinds.

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74. Theorem.—*The sum of the angles of a triangle is two right angles.*

Ill.—Cut out any triangle from a piece of paper. Then cut off two of the angles, as 1 and 2, and turn them about and place them by the side of the other angle, as in the lower figure. You will then see that *the line* OP *is straight,* and that the three angles of the triangle just make up the two right angles OED and PED.

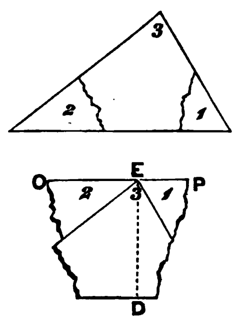

Fig. 52.

Ex. 1. If one angle of a triangle is a right angle, what is the sum of the other two?

Ex. 2. Can a triangle have more than *one* right angle? If two of its angles were right angles, what would the third angle be?

Ex. 3. Can a triangle have more than one obtuse angle?

SUG.—Try and see if you can draw a triangle with two right angles, or two obtuse angles.

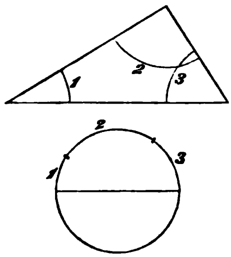

FIG. 53.

Ex. 4. Construct any triangle, and draw arcs measuring its angles. Then draw a circle *with the same radius* as the one used to measure the angles, and lay off upon the circumference the arcs measuring the angles. The sum of these arcs will always make up just a semi-circumference. What does this show?

Ex. 5. If two angles of one triangle are equal to two angles of another, can the third angles be unequal? Why?

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75. Prob.—*To make two triangles just alike.*

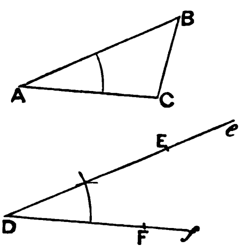

FIG. 54.

SOLUTION.—There are three ways of doing this:

1st Way.—Suppose I have any triangle, as ABC, and want to make another just like it. I first draw an arc measuring any one of the angles, as A, of the given triangle. Then I make an angle D equal to the angle A, and draw the sides D*e* and D*f*. Now I measure DE = AB, and DF = AC. If I now draw EF, the triangle DEF will be just like ABC, so that, were I to cut them out, I could apply one like a pattern to the other, and it would just fit.

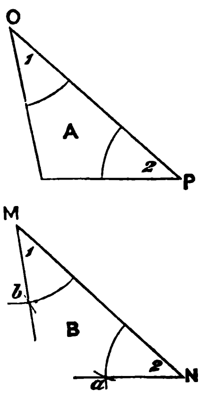

FIG. 55.

2d Way.—I have a triangle A, and wish to make another just like it. I draw arcs measuring any *two* of its angles, as O and P. Then, making a line MN equal to OP, I make an angle at M equal to O, and one at N, on the same side of MN, equal to P. Now making these two sides M*b* and N*a* long enough to meet (or, as we say, "producing them till they meet"), I have a second triangle, B, just like the first triangle, A. Were I to cut out the first triangle, it would fit on the second just like a pattern.

3d Way.—I have a triangle ACB, and want to make another just like it. I make a line DE equal to some side of the given triangle, as AB. Then taking AC as radius, I describe an arc from D as a centre, and in like manner, with BC as radius and E as a centre,

describe another arc. Through the intersections of these arcs, as F, I draw DF and EF. The triangle DEF is just like ABC. [Try it by drawing as described, and then cutting out one triangle, and seeing if you cannot fit it as a pattern on the other.]

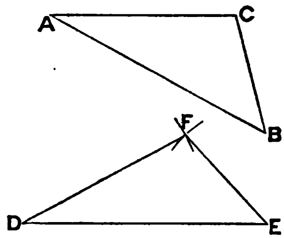

Fig. 56.

Ex. 1. In any triangle, which side is opposite the greatest angle? Which opposite the least angle?

Ex. 2. If you have two triangles with an angle in each equal, but the sides about this angle longer in one triangle than in the other, can you make one fit on the other as a pattern? Cut out two such triangles and try it.

Ex. 3. Can you make a triangle so that one of its sides shall be as long as both the others, or longer than both?

Ex. 4. Can you make a triangle so that one of its sides shall be less than the difference between the other two, or equal to the difference?

Ex. 5. If you have two triangles with *only* one side and one angle in the one equal to one side and one angle in the other, can you apply one as a pattern and make it fit on the other? Cut out two such triangles and try it.

Ex. 6. If you have two triangles with *only* two sides of one respectively equal to two sides of the other, can you make one fit as a pattern on the other? Try it.

Ex. 7. If you have two triangles with two sides in one equal respectively to two sides in the other, and the included angle in one greater than in the other, how is it with the third sides of the triangles?

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76. Theorem.—*The lines which bisect the angles of a triangle meet within the triangle at a common point.*

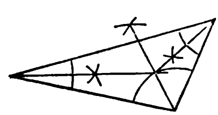
Fig. 57.

Ill.—Try it, by drawing a triangle, and then bisecting its angles, as taught in (*65*). You will need to do it very neatly, or the lines will not meet. It is a delicate operation. Try it in various forms of triangles, as equilateral, right angled, scalene, obtuse angled, etc.

77. Theorem.—*The lines drawn from the vertices of a triangle to the middle of the opposite sides meet in a common point within the triangle.*

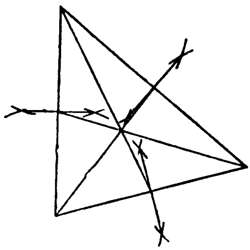

FIG. 58.

ILL.—Draw a triangle. Bisect each of the sides as taught in (*39*). Then join each angle and the middle of its opposite side with a straight line. If you do the work well, the three lines will cross each other at a common point within the triangle.

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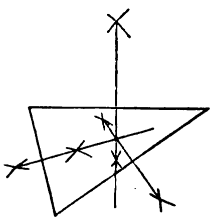
78. Theorem.—*The perpendiculars which bisect the sides of a triangle meet at a common point, which may be within or without the triangle, or in one of its sides, according to the form of the triangle.*



ILL.—Draw *an acute angled triangle*, and bisect its sides by perpendiculars. If you do it with accuracy, they will meet at a common point *within* the triangle.

Draw an *obtuse angled triangle*, bisect its sides with perpendiculars, and they will meet at a common point *without* the triangle.

Draw a *right angled triangle*, and the perpendiculars will meet in the side opposite the right angle (the hypotenuse).

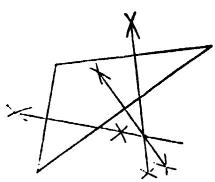


FIG. 59.

Ex. 1. Draw an *equilateral* triangle, and find the three points characterized in the last three articles. Are they all in one place, or are they in different places?

Ex. 2. Draw a scalene triangle, and find the three points as above. Are they all in the same place, or are they in different places?

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79. Prob.—*To inscribe a circle in a given triangle.*

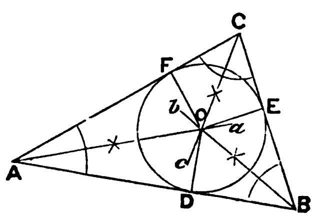

FIG. 60.

SOLUTION.—I wish to inscribe a circle in the triangle ABC; that is, a circle to which the sides of the triangle shall be tangents. [First draw the triangle.] I bisect the angles as taught in (*65*); and then from the point O, where these intersect, I let fall perpendiculars upon the sides, as taught in (*45*). Then from O as a centre, with a radius equal

to one of these perpendiculars (they are all equal), I draw a circle, and it is the circle required.

---

80. Prob.—*To circumscribe a circle about a given triangle.*

SOLUTION.—I wish to circumscribe a circle about the triangle ABC which I have drawn. To do this, I *bisect the sides* with perpendiculars, and find their common intersection O, as taught in (*78*). With O as a centre and a radius equal to OB, the distance from O to the vertex of any one of the angles, as these distances are all equal, I draw a circle. This is the circumscribed circle, that is, the circle in whose circumference the vertices of the triangle lie. [This is really the same as PROB. (*58*).]

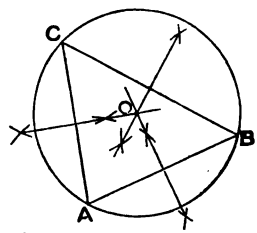

FIG. 61.

SECTION V.

ABOUT EQUAL FIGURES.

81. Equal, in geometry, signifies alike in all respects, *i. e.,* of the same shape and the same size.

82. Equivalent figures are such as have the same area, *i. e.,* are of the same size, irrespective of their form.

Ex. 1. Can a triangle be *equal* to a circle? Can it be *equivalent?* Can a circle be equivalent to a square? Can it be equal to a square?

Ex. 2. Can a right angled triangle be equal to an equilateral triangle? Can a right angled triangle be equal to an isosceles triangle? If either is possible, construct figures illustrating it.

---

83. Prob.—*To apply one straight line to another.*

SOLUTION.—[*Applying* figures to each other is a very important thing in geometry, and may seem a little curious at first; but it is, in reality, very simple. The pupil must become perfectly familiar with it.] We will first apply the line AB to the equal line CD. Take the line AB,* and placing the end A upon the end C of the line CD, make the line AB take the same direction as CD, and put the former upon the latter. Now, since the lines are equal, the

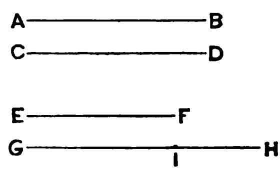

FIG. 62.

* That is, *think* about it just as if it were a little rod which you could pick up and handle.

extremity (or the point) B will fall upon D, and the two lines will coincide throughout their whole extent.

Again, we will apply the line EF to the line GH. Taking the line EF (*think* of it as a little rod which you can pick up and handle), put the point E upon G, and making the line EF take the same direction as GH, put the former upon the latter. Now, since EF is shorter than GH, the point (extremity) F will fall somewhere on the line GH, as at I. Therefore the lines do not coincide throughout their whole extent, and are not equal.

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84. *Prob.—To apply one plane angle to another.*

Solution.—First we will apply one angle to another equal angle. Thus, to apply BAC to the equal angle EDF. Take the angle BAC (*think* of it as if it were two little rods put firmly together at this angle, and so that you could pick them up and handle them), and placing the vertex (point) A upon the vertex (point) D, make the side AC take the *direction* DF. As AC happens to be longer than DF, the extremity C will fall beyond F, at some point, as O. But we do not care for this, as the size of an angle does not depend upon the length of the sides. Now, while A lies on D, and the line AC on DF, let the line AB be conceived as lying in the plane of the paper also (*i. e.*, on it). Since the angle BAC is equal to EDF, the line AB will take the direction DE, and will fall on it, though the point B will fall somewhere beyond E, as at N, as AB chances to be longer than DE. The two angles therefore coincide, and are equal. [Notice carefully just what is meant by saying that the angles are equal. We do not mean that the sides are of the same length, but that the *opening* between them is the same, *i. e.*, that one is just as sharp a corner as the other.]

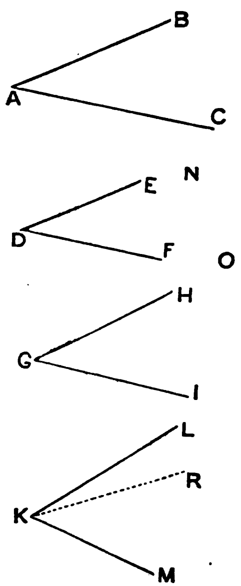

Fig. 63.

Queries.—If BAC were greater than EDF, and we should begin by putting A upon D, and make AC fall upon DF, where would AB fall, without the angle EDF or within it? If BAC were less than EDF, and we proceed as before, placing the vertex A on D, and AC on DF, would AB fall without EDF or within it?

Again, let us attempt to apply the angle HGI to LKM. Placing the vertex G on the vertex K, making the side GI take the direction KM, and then bringing GH into the plane of the paper, the side GH will fall within the angle LKM (as in the line KR), since the angle HGI is less than LKM. The angles, therefore, do not coincide.

85. Prob.—*When two triangles have two sides and the included angle of one equal to two sides and the included angle of the other, to apply one triangle to the other.*

SOLUTION.—In the two triangles ABC and DEF, let the angle A be equal to the angle D, the side AB = the side DE, and AC = DF. We will apply the triangle ABC* to DEF. Take the triangle ABC and place the vertex A upon the vertex D, making the side AC take the direction DF. Since AC = DF, the extremity C will then fall on F.† Now bring the triangle ABC into the plane of DEF, keeping AC in DF, and the line AB will take the direction DE, since the angle A = the angle D. Again, as AB = DE, the extremity B will fall upon E. Thus we have placed ABC upon DEF, so that A falls upon D, C upon F, and B upon E, and find that they exactly coincide.

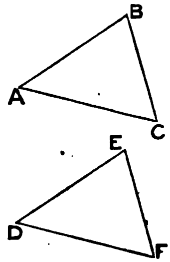

FIG. 64.

Ex. 1. Suppose you attempt to apply ABC in the last figure to DEF by placing B on D, and letting BC fall upon DF. Where will C fall? Measure it and find out. Which side will then fall nearly or quite on DE? Will it fall exactly on it? On which side will it fall? Can you make the triangles coincide (fit) in this way?

Ex. 2. Can you make the triangles in the last figure coincide by placing C upon D, and letting CA fall upon DF? Where will A fall? What line will fall on or near DE? Will it fall without DE, or within?

Ex. 3. Construct two isosceles triangles,‡ as ACB and DEF, in which AC = CB = DE = EF. Can you apply DEF to ABC by putting D upon A? Describe the process. Can you put D upon A and DE upon AB, and make the triangles coincide? Can you make the triangles coincide by putting F upon A? If so, describe the process. Can you make them coincide by putting E upon A? If not, point out the difficulties.

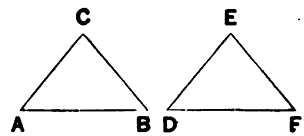

FIG. 65.

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* Think of ABC as made of little rods, so that you can pick it up and place it upon DEF in the manner described.

† It will make it clearer if the pupil thinks of ABC, at this stage of the operation, as having the side AC on DF, but the angle B not down on the paper; just as if he were to cut out ABC, and set the edge AC on the line DF, and *afterward* bring the triangle ABC down on to DEF, keeping the edge AC on the line DF.

‡ The teacher must insist upon the figures being drawn, and that accurately, according to rule.

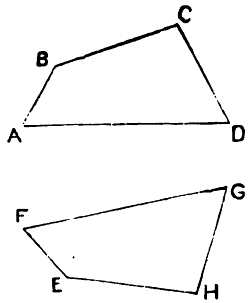

Fig. 66.

Ex. 4. Construct two equal trapeziums,* as ABCD and EFGH, and describe the process of applying one to the other.

Solution.—I will apply EFGH to ABCD. As the angle E is equal to the angle B, I will begin by putting the vertex E on B, and making EH fall upon BC. Since EH = BC, H will fall on C. Now, as angle H = angle C, HG will take the direction (fall on) CD; and since HG = CD, G will fall on D. Again, as G = D, GF will take the direction DA; and since GF = DA, F will fall on A. Finally, as F = A, FE will take the direction AB; and since FE = AB, E will fall on B, as it ought, since I started by conceiving E as placed on B.

Ex. 5. Describe the application of ABCD in the last figure to EFGH, by beginning with C upon H.

Ex. 6. Having two equal equilateral triangles, can you apply one to the other by beginning indifferently with any one angle of one upon any one angle of the other? Draw two such triangles, and go through with the details of the application.

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86. Prob.—*Given two triangles with two angles and the included side of the one respectively equal to two angles and the included side of the other, to apply one triangle to the other.*

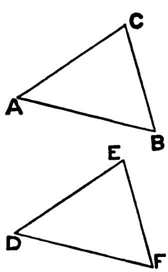

Fig. 67.

Solution.—[The pupil should first draw any triangle, as ABC. Then make a line DF equal to AB, and at the extremities D and F make angles, as D and F, respectively equal to A and B. This is preliminary.] Having the two triangles ABC and DEF, in which A = D, B = F, and AB = DF, I propose to apply one to the other. I will apply ABC to DEF. Taking ABC, I place A upon D, and make AB take the direction and fall upon DF. Since AB = DF, B will fall upon F. Now keeping the line AB in DF, I conceive the triangle ABC to come into the plane of DEF. Since A = D, the side AC will take the direction DE, and the extremity C of AC will fall somewhere in the line DE, or in DE produced. Also, since B = F, the line BC will take the direction FE, and the extremity C of BC will fall somewhere in FE or FE produced. Finally, as C falls in DE and

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* The teacher must insist upon the figures being drawn, and that accurately, according to rule.

FE both, it must be at E, their intersection. Thus I find that the triangle ABC, when applied to DEF, coincides with it throughout.

Ex. 1. Given the two triangles DEF and ABC, in which DE=AB, D = A, but E > B; show how an attempt to apply one to the other fails.

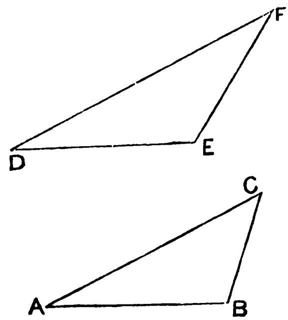

Fig. 68.

SOLUTION.—Since angle D = angle A,* I apply the vertex D to the vertex A, and make DE take the direction AB. As DE = AB, E will fall on B, and the sides DE and AB will coincide. Again, since D = A, the side DF will take the direction AC when the planes of the triangles coincide; and the extremity F will fall in AC, or in AC produced (really in AC produced, in this case). Finally, since E > B, EF will fall to the right of BC, and the application fails.

Ex. 2. Construct two trapeziums with their respective sides equal, as AC = HE, AB = HG, BD = GF, and CD = EF, but with their angles unequal; and show how an attempt to apply one to the other fails.

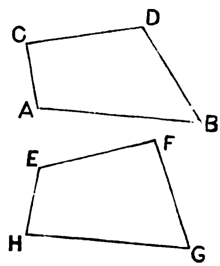

Fig. 69.

Ex. 3. If the sides of two trapeziums, as in the last figure, are equal, and two of the angles including a side in one are respectively equal to the corresponding angles in the other, as A = H, and B = G, can one be applied to the other? If so, give the details of the process.

SECTION VI.

ABOUT SIMILAR FIGURES, ESPECIALLY TRIANGLES.

87. ***Similar Figures*** are such as are shaped alike—*i. e.*, have the same form.

A more scientific definition is, *Similar Figures* are such as have their angles respectively equal, and their homologous (corresponding) sides proportional.

* Be careful to distinguish between the vertex, which is a point, and the angle, which is the *opening* between the lines.

88. Homologous, or Corresponding Sides of similar figures, are those which are included between equal angles in the respective figures.

IN SIMILAR TRIANGLES, THE HOMOLOGOUS SIDES ARE THOSE OPPOSITE THE EQUAL ANGLES.

ILL.—The triangles ABC and DEF are similar, for they are of the same shape. But it is easy to see that ABC is not similar to IHK or MON. The pupil should notice that A = D, C = F, and B = E. Also, side e is $1\frac{1}{3}$ times b, side f is $1\frac{1}{3}$ times c, and side d is $1\frac{1}{3}$ times a; so that $f : c :: e : b$, and $f : c :: d : a$, and $d : a :: e : b$. Now there are no such relations existing between the parts of ABC and IHK. The angles B and K are nearly equal, but A is much larger than H, and C is smaller than I. So these triangles are *not* mutually equiangular, *i. e.*, each angle in one has not an equal angle in the other. Again, as to their sides, IH is a little less than AC, but HK is greater than AB. These two triangles are, therefore, not similar.

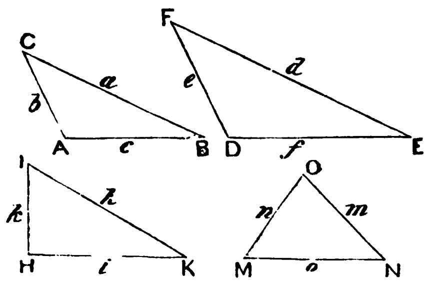

FIG. 70.

In the similar triangles ABC and DEF, b is homologous with e, since they are opposite the equal angles B and E. For a like reason a is homologous with d, and c with f. It may also be observed, that the shortest sides in two similar triangles are homologous with each other; the longest sides are also homologous with each other, and the sides intermediate in length are homologous with each other.

Ex. 1. Can a scalene triangle be similar to an isosceles triangle? Can an obtuse angled triangle be similar to a right angled triangle?

Ex. 2. Are all squares similar figures?

SUG.—First, are the angles equal? Second, is any one side of one square to some side of another square as a second side of the first is to a second side of the second, etc.?

Ex. 3. A farmer has two fields, each of which has 4 sides and 4 right angles. The first field is 20 rods by 50, and the other 40 by 80. Are they similar?

SUG.—Are they mutually equiangular? Then are the lengths in the same ratio as the widths? If they are not similar, how long would the second have to be in order to make them similar? Draw two such figures, and see if they look alike in shape.

89. *Prob.*—*To find a fourth proportional to three given lines.*

SOLUTION.—I have the three given lines A, B, and C, and wish to find a fourth line such that

A shall be to B as C is to the *fourth line*, *i. e.*,

A : B : : C : *fourth line.*

To do this, I draw two indefinite lines OX and OY, from a common point O. On one of these, as OX, I lay off Oa = A, and Oc = B. Then on the other I make Ob = C, and draw ab. Finally, drawing a parallel to ab through the point c (67), I have Od as the line sought. Thus, calling Od, D, the proportion is

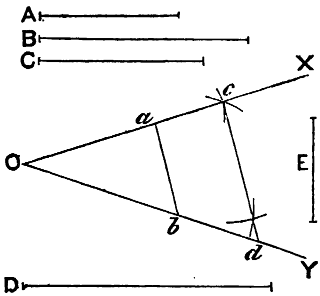

FIG. 71.

Oa : Oc : : Ob : Od, or
A : B : : C : D.

N.B.—*The order in which the lines are taken, and the way of drawing the lines ab and cd, are essential.* The following directions will insure correctness : *Lay off the* FIRST *and* SECOND *on the* SAME LINE, as on OX; *and the* THIRD *on the* OTHER LINE, as on OY. *Then join the extremities of the* FIRST *and* THIRD, *and draw the parallel through the extremity of the* SECOND.

Ex. 1. Show that if the order of the proportionals in *Fig.* 71 is B : A : : C : *fourth line*, the fourth proportional is E, *Fig.* 71.

Ex. 2. Show that a fourth proportional to A, B, and C is D. Also, that a fourth proportional to C, A, and B is E. Show that, if the order be A : C : : B : *fourth line*, D is still the fourth proportional. Show that B : C : : A : 2C, nearly.

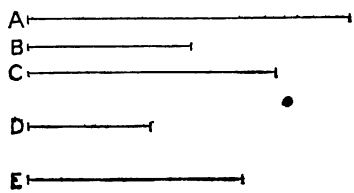

FIG. 72.

Ex. 3. Solve the proportion 3 : 8 : : 5 : x, and find x geometrically.

SUG.—Using the scale of 100ths of a foot, the figure is that in the margin. OD is the fourth proportional, or x = OD, which is found *by measurement* to be 13⅓, as it is by arithmetic.

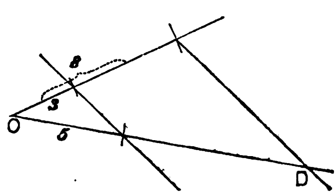

FIG. 73.

***90. Prob.**—To draw a triangle similar to a given triangle, and having a given side.*

SOLUTION.—*1st Method.*—I have a triangle ACB, and want to make another similar to it, but having the side homologous to BC equal to *a*. I draw an indefinite line, and on it take EF, equal to *a*. Then at F I make an angle equal to C, and make the side indefinite. Now I find a fourth proportional to BC, EF, and AC. Having found this, as in the last article, I lay it off from F, as FD. Drawing DE, I have DEF, the triangle required.

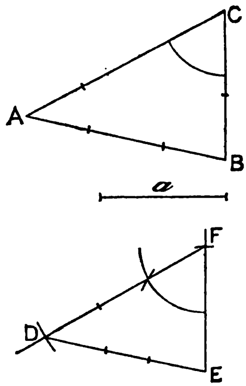

FIG. 74.

I can readily satisfy myself that DEF is similar to ABC, for besides the fact that it looks as if it were of the same shape, by measuring the other two angles, I find that E = B, and D = A. Moreover, I know that BC, EF, AC, and DF are proportional, because I made them so. And, by finding a fourth proportional to BC, EF, and AB, I find it exactly equal to DE. In like manner constructing a fourth proportional to AC, DF, and AB, I find it to be DE. So that the two triangles are mutually equiangular, and have their homologous sides (those opposite the equal angles) proportional. Hence, the triangles are similar.

2d Method.—But an easier way to construct DEF is to make the angle F = C as before, and then make E = B, and produce the sides till they meet in D. The triangles will then be similar, and the proportionality of the sides can be tested.

Ex. 1. Given a triangle whose sides are 7, 11, and 15, to construct a similar triangle having the side corresponding to the one which is 11 in the given triangle, 8.

Ex. 2. Construct two triangles with equal angles, and then compare the sides, and see whether you can make two triangles whose angles shall be respectively equal, and their sides not be proportional.

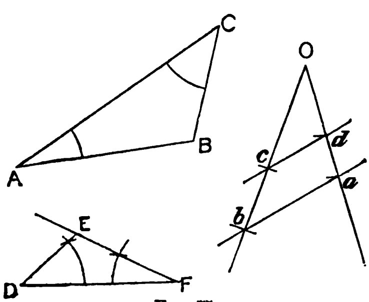

FIG. 75.

SUG.—Having the triangle ABC, make DEF equiangular with it, and then compare the homologous sides. In the figure D is made equal to C, and F to A; whence E = B. DE and BC are homologous sides, because opposite the equal angles F and A. DF is homolo-

gous with AC, because it is opposite angle E, which equals B. For a similar reason EF is homologous with AB. Now, taking two sides of ABC, as BC and AB, and a side of DEF homologous with one of them, as DE, and finding a fourth proportional Oc, it will be found exactly equal to EF; so that

$$\mathrm{BC} : \mathrm{DE} :: \mathrm{AB} : \mathrm{EF}\ (= \mathrm{O}c).$$

Ex. 3. Make two triangles, two of whose angles shall be, one $\frac{2}{3}$ and the other $\frac{1}{4}$ of a right angle; but make the side included between these angles twice as great in the second triangle as in the first. What will be the ratio of the side opposite the angle $\frac{2}{3}$ in the first triangle to the homologous side in the second? What the relation of the sides opposite the angles $\frac{1}{4}$?

Ex. 4. If you make one triangle whose sides are 5, 8, and 3; and a second whose sides are 15, 24, and 9, will they be mutually equiangular? Which angles are the equal ones? Which are the homologous sides?

Ex. 5. There are three pairs of similar triangles in *Fig.* 76. Can you point them out? Also point out their homologous parts. Are all the triangles which you can make out from the figure similar to each other?

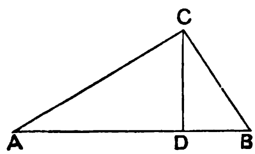

FIG. 76.

Ex. 6. Wishing to know the height EC of a house, I set up a stake DB 5 feet long; and putting my eye close to the ground, I moved back from the stake to A, so that the top of the stake and the top of the house were just in range (in a line). Then by measuring I found AB = 10 feet, and AC = 80 feet. What was the height of the house?

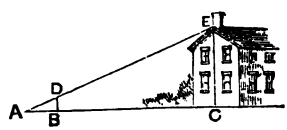

FIG. 77.

Ex. 7. If you take three sticks of different lengths and put them together by joining their ends two and two, so as to represent a triangle; can you, by putting together the same sticks in a different order, make a triangle of different form from the first? Will the angles opposite the same sticks always be the same?

Ex. 8. If you take more than three sticks (say 4), and make of them the boundary of a figure, by putting their ends together two and two, can you put them together so as to make another figure of different form? Can you make figures having different angles?

Ex. 9. If you take three sticks, A 3 inches long, B 5 inches,

and C 6 inches; and also three other sticks, D 9 inches long, E 15 inches, and F 18 inches;* can you place them together so as to make dissimilar triangles? Will the corresponding angles of the two triangles be equal however you may arrange the sticks? If the sides of two triangles are proportional, will their angles be equal and the triangles similar?

Ex. 10. If you take four sticks, A 3 inches long, B 5 inches, C 6 inches, and K 4 inches; and also four other sticks, D 9 inches long, E 15 inches, F 18 inches, and L 12 inches;* can you place them together so as to make four-sided figures which shall be dissimilar (*i. e.*, not of the same shape)? Will the corresponding angles of the two figures be necessarily equal? If the sides of a four-sided figure are proportional, does it follow that the corresponding angles are equal, and the figures similar?

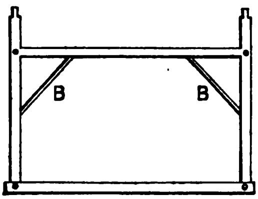

FIG. 78.

Ex. 11. Why do the braces in the frame of a building stiffen it? Is a four-sided figure stiff? *i. e.*, are its angles incapable of change while its sides remain of the same length? Can the angles of a triangle be changed while the sides remain unchanged?

SECTION VII.

ABOUT AREAS.

91. A Quadrilateral is a plane surface inclosed by *four* right lines.

92. There are three *Classes* of quadrilaterals, viz., *Trapeziums*, *Trapezoids*, and *Parallelograms*.

93. A Trapezium is a quadrilateral which has no two of its sides parallel to each other.

94. A Trapezoid is a quadrilateral which has but two of its sides parallel to each other.

* Notice that the sides are proportional, *i. e.*, in the same ratio taken two and two.

95. *A Parallelogram* is a quadrilateral which has its opposite sides parallel.

96. *A Rectangle* is a parallelogram whose angles are right angles.

97. *A Square* is an equilateral rectangle.*

98. *A Rhombus* is a parallelogram whose angles are not right angles, and all of whose sides are equal.

99. *A Rhomboid* is a parallelogram whose angles are not right angles, and two of whose sides are greater than the other two.

ILL.—The figures in the margin are all quadrilaterals. A is a trapezium. (Why?) B is a trapezoid. (Why?) C, D, E, and F are parallelograms. (Why?) D and E are rectangles, although D is the form usually referred to by the term rectangle. So C is the form usually referred to when a parallelogram is spoken of, without saying what kind of a parallelogram. C is also a rhomboid. (Why?) E is a square. (Why?) F is a rhombus. (Why?) This page is a rectangle; so also are the common panes of glass.

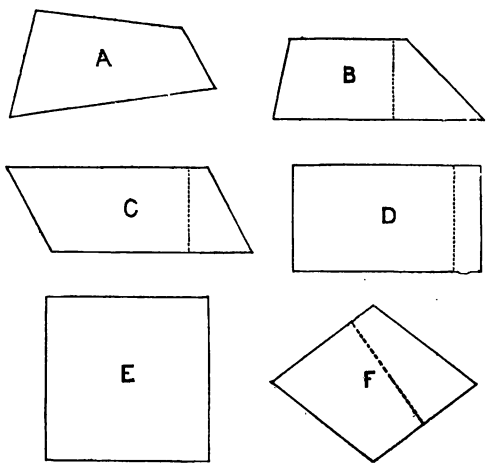

FIG. 79.

100. *A Diagonal* is a line joining two angles of a figure, not adjacent.

ILL.—In common language, a diagonal is a line running "from corner to corner."

EX. 1. To construct a square, having given a side; or, in other words, to construct a square on a given line.

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* The pupil should be able to give this and all similar definitions *at length*. Thus, A Square is a surface inclosed by four equal right lines making right angles with each other.

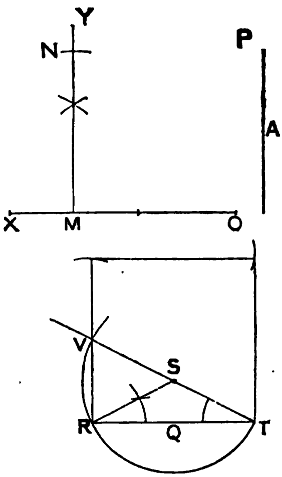

FIG. 80.

1st Method.—Let **A** be the given side. Draw the indefinite line **OX**, and lay off **OM** = **A**. At **M** erect a perpendicular **MY**, as taught in (**44**). On this take **MN** = **A**. From **N** and **O** as centres, with a radius equal to **A**, describe arcs intersecting, as at **P**. Draw **NP** and **PO**.

2d Method.—Let **Q** be the given side. Construct equal angles at the extremities of **Q**, and produce the sides till they meet, and one of them till it will meet another side of the square proposed. With **S** as a centre, and **ST** or **SR** as radius, describe a semicircle. Draw **RV**, and it forms a right angle at **R**. The construction can now be finished as before.

Ex. 2. Construct a rhombus whose side is 2 inches, and one of whose acute angles is $\frac{2}{3}$ of a right angle.

Ex. 3. Construct a rectangle whose adjacent sides are 3 and 5.*

Ex. 4. Construct a rhomboid whose adjacent sides are 3 and 7, and their included angle $\frac{1}{2}$ a right angle.

Ex. 5. How many diagonals has a triangle? How many has a quadrilateral? How many has a figure with five sides (a pentagon)? Of six? Of eight?

---

101. The Area of a surface is the number of times it contains some other surface taken as a unit of measure; or it is the ratio of one surface to another assumed as a standard of measure.

102. The *Unit of Area* usually assumed is a square, a side of which is some linear unit: thus, a *square inch*, a *square foot*, a *square yard*, a *square mile*, etc. By these terms is meant a square 1 inch on a side, one foot on a side, one yard on a side, etc.

The acre is an exception to the general rule of assuming the square on some linear unit as the unit of area, there being no linear unit in use whose length is the side of a square acre.

ILL.—The area of a board is the number of squares 1 foot on a side which it would take to cover it. The area of a floor may be spoken of in square yards, and is the same as the number of square yards of carpeting it would take to cover it.

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* Take any convenient unit, as $\frac{1}{4}$ inch, 1 inch.

103. *The Altitude* of a parallelogram is the distance between its opposite sides; of a trapezoid, it is the distance between its parallel sides; of a triangle, it is the distance from any vertex to the side opposite or to that side produced.

104. *The Bases* of a parallelogram or of a trapezoid are the sides between which the altitude is conceived as taken; of a triangle, it is the side to which the altitude is perpendicular.

ILL.—The dotted lines in B, C, D, and F, *Fig.* 79, represent altitudes. When the altitude is the distance between two parallels, the figure has two bases. The altitude of a parallelogram may be reckoned between either pair of parallel sides, but it is most common to conceive it as the distance between the two longer sides. The altitude of a rectangle is the same as either side to which it is parallel. A triangle may have three altitudes, and any side of a triangle may be conceived as its base. In *Fig.* 81, AB is conceived as the base in each case, and CD the altitude.

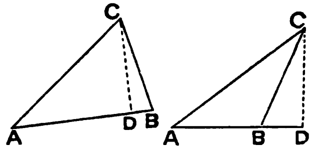

FIG. 81.

Ex. What side of a triangle must you conceive as the base, in order that the altitude shall fall upon it, and not upon its prolongation? From what angle will the altitude be reckoned in such a case?

---

105. *Theorem.*—*The area of a rectangle is the product of its two adjacent sides; or, what is the same thing, the product of its altitude and base.*

ILL.—Let ABCD represent a rectangle, of which AB is 8 units long, and AC 5. Now, let us conceive a square *a* constructed on one of these units. Using this surface as the unit of area, it is evident that in the rectangle *c*AB*d* there will be 8 such. Hence, the area of this rectangle is 8 (square units). Now, drawing parallels to the base through the several points of division of the altitude, it is evident that the whole rectangle ABCD is made up of as many rectangles like *c*AB*d* as there are units in the altitude—in this case 5. Hence the whole area is 5 times the area of *c*AB*d*, *i. e.*, 5 times 8 (square units) = 40 (square units).

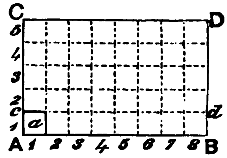

FIG. 82.

N.B.—*The pupil should be careful to observe that the language "product of base into altitude," is only a convenient form of abbreviated expression.* It is

just as absurd to talk about multiplying a line by a line, as to talk about multiplying dollars by dollars. Thus 8 inches in length can be taken 5 times, and makes 40 inches in length. But what does 8 inches in length, multiplied by 5 inches *in length* mean? Or what is 8 dollars taken 5 *dollars* times? The multiplier must always be an abstract number, and the product be like the multiplicand, from the very nature of multiplication. With this the explanation given above agrees. When we say that the area of ABCD $= 8 \times 5$, we mean 5 times 8 square units, which equals 40 square units.

---

106. Theorem.—*The area of any parallelogram is the same as the area of a rectangle having the same base and altitude as the parallelogram, and hence is the product of its base and altitude.*

ILL.—This truth is easily illustrated by cutting out a parallelogram, as ABCD. Then, cutting off the triangle DEC, being careful to make DE perpendicular to BC, and placing DC upon AB so as to bring the triangle DEC into the position AFB, the two parts will just make up the rectangle AFED. Hence we see that the area of ABCD is the same as the area of AFED, which latter is a rectangle having the same base AD, and the same altitude ED, as the given parallelogram.

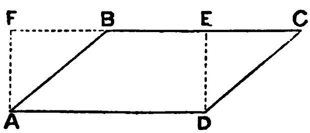

FIG. 83.

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107. Theorem.—*The area of a triangle is half the product of its base and altitude.*

ILL.—To illustrate this truth, cut out two triangles A and B *just alike*. By placing them together, a parallelogram can be formed whose base and altitude are the same as the base and altitude of the triangle. The area of the parallelogram is the product of its base and altitude. Hence the area of one of the triangles is one-half the product of its base and altitude.

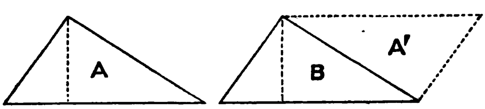

FIG. 84.

In fact, by cutting one of the triangles, as A, into two triangles, its parts can be put with B so as to make a *rectangle* having the same base and altitude as the triangles. [The pupil should do it.]

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108. Theorem.—*The area of a trapezoid is the product of its altitude into the line joining the middle points of its inclined sides.*

ILL.—To illustrate this truth, cut out any trapezoid, as ABCD, and through

the middle of the inclined sides, as a and b, cut off the triangles Aam and Bbn, being careful to cut in lines am and bn perpendicular to the base. These can be applied as indicated in the figure, so as to fill out the rectangle $omnp$. Hence we see that the area of the trapezoid is just equal to the product of its altitude into the line joining the middle points of its inclined sides, as ab.

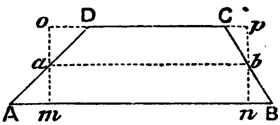

FIG. 85.

Ex. 1. How many square yards of plastering in the walls of a room 20 feet by 30, and 15 feet high, including the ceiling?

Ans. $233\frac{1}{3}$.

Ex. 2. A salesman is selling a piece of velvet which is worth $8 per yard. The velvet is cut "on the bias," as the technical phrase is, *i. e.*, obliquely, instead of square across. The piece he is selling is measured along the selvedge in the usual way half a yard. He is disposed to charge the customer somewhat more than $4. Is he right? The customer claims that he is getting but half a yard of velvet, and so ought to pay but $4. Is he right?

Ans. Both are right,—the salesman in his demand, and the customer in his statement. How is it?

Ex. 3. There are two parallel roads one mile apart. A has a farm which extends along one of the roads half a mile, and the lines run perpendicularly from one road to the other. B has a farm lying between the same roads, and half a mile front on each road, but running obliquely across. Which has the larger farm?

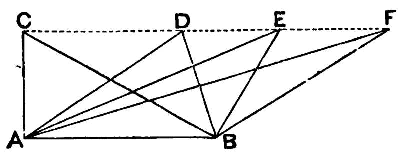

FIG. 86.

Ex. 4. Of the four triangles ACB, ADB, AEB, and AFB, *Fig.* 86, which has the greatest area, CF being parallel to AB?

Ex. 5. Which is the largest triangle which can be inscribed in a semicircle, having the diameter for its base?

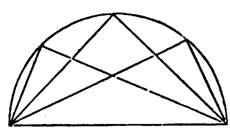
FIG. 87.

Ex. 6. Can you vary the area of a triangle while the sides remain of the same length? Can you vary the area of a quadrilateral while the sides remain of the same length?

Ex. 7. If you have two lines each 5 inches long, and two each 3 inches long; into what kind of a parallelogram must you form them in order to have its area the greatest?

Ex. 8. Rough boards are usually narrower at one end than at the other, for which reason the lumberman measures their width in the middle. What is the number of square feet in the following:

12 boards 16 feet long, 10 inches wide (in the middle);
15 boards 11 feet long, 9 inches wide " " ;
8 boards 10 feet long, 13 inches wide " " ?

What principle is involved in such measurement?

Ex. 9. What is the area of a triangle whose altitude is 6 feet, and base 10 feet? Are these elements sufficient to fix the *form* of the triangle?

Ex. 10. If a line be drawn from any angle of a triangle to the middle of the opposite side, what is the relation of the areas of the two partial triangles? Why?

THE PYTHAGOREAN PROPOSITION.

109. *Theorem.*—*The square described on the hypotenuse of a right angled triangle is equivalent to the sum of the two squares described on the other two sides.*

ILL.—The meaning of this proposition may be illustrated thus: Let ABC be a right angled triangle, right angled at C, and the sides AC and CB be 4 and 3 respectively. Then measuring AB, it will be found to be 5, and we observe that $4^2 + 3^2 = 5^2$. This is also seen from the figure, in which the square on AC contains $4^2 = 16$ square units, and that on CB $3^2 = 9$; while that on AB contains $5^2 = 25$, *i. e.*, as many as on both the other sides. We cannot so readily *illustrate* the truth of the proposition when the ratio of the sides is any other than that of 3, 4, and 5, but it is equally true in all cases, as will be proved in the next part of this book.

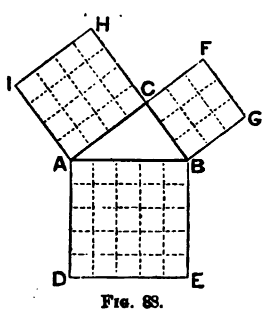

FIG. 88.

Ex. 1. Can you make a right angled triangle whose sides shall be 5, 8, and 10?

SUG.—As 10 is the longest side, it will have to be the hypotenuse. Now $5^2 + 8^2 = 25 + 64 = 89$. But $10^2 = 100$. Hence, 10 is too long for the hypotenuse of a right angled triangle whose other sides are 5 and 8.

Ex. 2. Can you make a right angled triangle whose sides shall be 9, 12, and 15?

Ex. 3. A carpenter has framed the four sills of a building together, and placed them on the foundation. He then wishes to adjust them so that the angles shall be right angles. He places one end of his ten foot pole ab at a, 6 feet from c; and, holding it in position, orders his attendants to move the sill AB to the right. How far will the end b of the pole be from c when the angle B is a right angle?

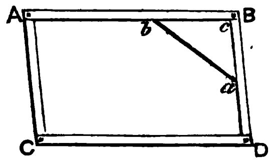

FIG. 89.

Ex. 4. A gate is to be 10 feet long and 4 feet high. How long must the brace be to go in as a diagonal and hold the gate in the form of a rectangle?

Ex. 5. The angles of a room are all right angles, and its dimensions are 20 feet by 30 on the floor, and 15 feet high. What is the length of the longest diagonal extending from one corner on the floor to the opposite corner in the ceiling?

Ans. A little more than 39 feet.

Ex. 6. The numbers 3, 4, and 5 are much used by artizans as parts of a right angled triangle. Will any equi-multiples of them answer the same purpose, as twice them, *i. e.*, 6, 8, and 10; or three times them, as 9, 12, and 15, etc.?

Ex. 7. In an obtuse angled triangle, is the square of the side opposite the obtuse angle greater or less than the sum of the squares of the other two sides? How is it with the square of the side opposite an acute angle?

SUG.—In the right angled triangle ABC, $\overline{AC}^2 = \overline{CB}^2 + \overline{AB}^2$. In the obtuse angled triangle C′B is equal to CB in the right angled triangle. But $\overline{AC'}^2$ is greater than $\overline{AC}^2$; hence $\overline{AC'}^2 > \overline{BC'}^2 + \overline{AB}^2$. By a similar inspection the other case may be determined.

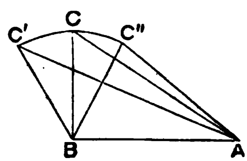

FIG. 90.

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110. Prob.—*To find a mean proportional between two lines.*

SOLUTION.—I wish to find a mean proportional between the lines M and N, *i. e.*, a line x, such that

$$M : x :: x : N, \text{ whence } x^2 = M \times N, \text{ and}$$
$$x = \sqrt{M \times N}.$$

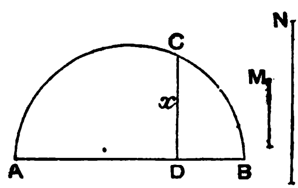

FIG. 91.

I draw a line AB equal to the sum of M and N, making DB = M, and AD = N. I draw a

semicircumference on AB, and at D erect CD perpendicular to AB. CD is x, the mean proportional required.

Ex. 1. To construct a square which shall be equal in area to a given rectangle.

Sug.—Draw any rectangle. Then find a mean proportional between its adjacent sides as described above. A square constructed on this line will be equal in area to the rectangle; since, if x is the side of the square, and M and N are the adjacent sides of the rectangle, $x^2 = M \times N$. But x^2 is the area of the square, and $M \times N$ is the area of the rectangle.

Ex. 2. To find the square root of 15 by means of the ruler and compasses.

Sug.—Since $15 = 3 \times 5$, if $DB = 3$ and $AD = 5$, *Fig.* 91, x (CD) $= \sqrt{3 \times 5} = \sqrt{15}$. Therefore, making a figure having DB and AD of these lengths, CD can be measured, and thus the square root of 15 obtained, approximately, in numbers.

N. B.—*In such a case* CD *represents exactly the required root, although we may not be able to express the value exactly in numbers.* In this case geometry does exactly what arithmetic can only do approximately.

Ex. 3. Draw a line which shall represent, exactly, the square root of 5.

Sug.—Make $DB = 1$, and $AD = 5$.

Ex. 4. Draw a rectangle whose adjacent sides are 2 and 3, and then draw a square of the same area.

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111. Theorem.*—The areas of similar triangles are to each other as the squares of their homologous sides.*

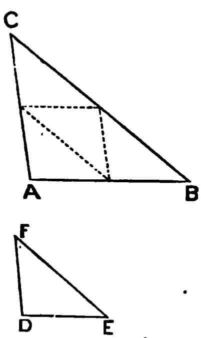

Fig. 92.

Ill.—The meaning of this is, that if ABC and DEF are similar, and any side of ABC is 2 times as great as the homologous side of DEF (as is the case in the figure, CB being = 2FE, CA to 2FD and AB to 2DE) the area of ABC is 4 times the area of DEF. In fact, in a simple case like this, we can divide ABC into four triangles exactly equal to DEF, as is done by the dotted lines.

Ex. 1. A and B have triangular pieces of land, which are similar to each other, and similarly situated. But A's front is to B's as 5 to 3; how much more land has A than B?

Ans. $2\frac{7}{9}$ times as much.

Ex. 2. In order that one triangle may be similar to and 4 times as great as another, how must any side of the first compare with the homologous side of the second?

Ex. 3. In order that the areas of two similar triangles may be to each other as 4 to 9, what must be the ratio of their homologous sides?

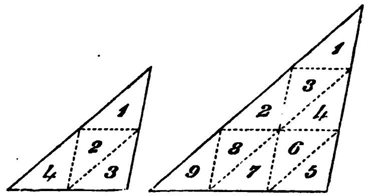

Fig. 93.

***112. Theorem.**—The homologous sides of similar triangles are to each other as the square roots of their areas.*

This theorem is involved in the theorem that the areas of similar triangles are to each other as the squares of their homologous sides. It is illustrated in the preceding examples.

Ex. Construct a triangle with one of its sides 2 in length. Then construct a similar triangle $1\frac{1}{2}$ times as large. What must be the length of the side of the second triangle which is homologous with the side 2 of the first.

Solution.—Let CAB be the given triangle, whose side AB is 2. Since the second is to be $1\frac{1}{2}$ times as great as the first, the ratio of the areas is 2 : 3. Hence, $\sqrt{2} : \sqrt{3}$ :: AB (or 2) : x, the side of the required triangle homologous with side 2 of the given triangle. Construct the square roots of 2 and 3, as ab and ac in the figure, and then find a fourth proportional to ab, ac, and AB. This is found to be ay. Taking DE = ay, construct on it a triangle DEF similar to ABC, and it will be $1\frac{1}{2}$ times as large.

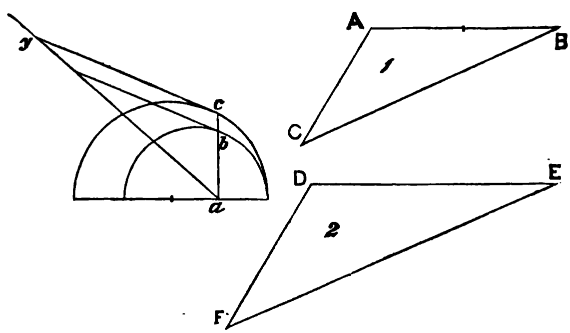

Fig. 94.

THE AREA OF A CIRCLE.

113. Theorem.—*The area of a circle whose radius is r, is* πr^2, *i.e.*, 3.1416 *times the square of its radius.*

ILL.—If we take a circle whose radius is r and circumscribe about it a square ABCD, we observe that the area of this square is $4r^2$. Hence we see that the area of a circle is *less* than 4 times the square of its radius. Again, drawing two diameters EF and GH at right angles to each other, and joining their extremities, we have the inscribed square GEHF. The area of this square is equal to the area of the two triangles GEF and EHF. But area $GEF = \frac{1}{2}GO \times EF = \frac{1}{2}r \times 2r = r^2$; and in like manner $EHF = r^2$. Hence area $GEHF = 2r^2$. We thus see that the area of a circle is *more* than two times the square of the radius. The area of a circle is therefore somewhere between two and four times the square of its radius. Just how many times r^2 the area is, we do not propose to find in this place, but only say that it has been found to be 3.1416 times r^2. We must also remark that this is not *exact;* but it is near enough for practical purposes. In fact, nobody knows exactly how many times the square of the radius the area of a circle is.

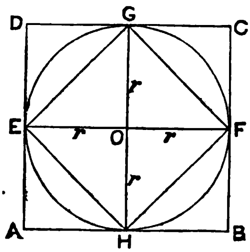

FIG. 95.

Ex. 1. If you cut from a square the largest possible circle, show that you cut away a little less than $\frac{1}{4}$ of the square, or more exactly .2146 of it.

Ex. 2. What is the area in acres of a circle whose diameter is 3 miles? *Ans.* 4523.904.

Ex. 3. A horse is so tied to a tree that he can graze on every side of it to a distance of 100 feet. What is the area in acres over which he can graze? *Ans.* A little less than $\frac{3}{4}$ of an acre.

Ex. 4. What is the area of a circle whose radius is 1?

[Remember this result.]

Ex. 5. What is the area of a circle whose radius is 2? 3? 4? How do these areas compare with the area of a circle whose radius is 1?

---

114. Theorem.—*The areas of circles are to each other as the squares of their radii.*

ILL.—This is readily seen from the last theorem. Thus the area of a circle whose radius is 5 is 25π; and of one whose radius is 6, the area is 36π. Now,

the ratio of these areas $25\pi : 36\pi$ is the same as $25 : 36$, *i.e.*, as the squares of the radii of the two circles.

Ex. 1. In the figure the radius of the outer circle is twice that of the inner. How do their areas compare? How do the 4 parts into which the larger circle is divided compare with each other?

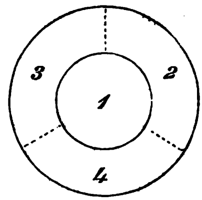

FIG. 96.

Ex. 2. The radii of 2 circles are 3 and 5 respectively; what is the relation of their areas?

Ans. 9 : 25; or one is $2\frac{7}{9}$ times as large as the other.

Ex. 3. I have a circle whose radius is 5, and wish to make another whose area is twice as great; what must be its radius?

Ans. $\sqrt{50}$, or 7.071 nearly.

Ex. 4. Can we compare the areas of circles by means of the squares of their diameters as well as by means of the squares of their radii? How much greater is the square of the diameter of any circle than the square of the radius?

Ex. 5. Two 5-inch stovepipes run together into one 7-inch pipe. Is the capacity of the one pipe equal to that of the two?

Ex. 6. Two men bought grindstones of equal thickness. The stones cost $4 and $9 respectively. One was 2 feet in diameter and the other 3. What was the difference in the rates paid?

SECTION VIII.

OF POLYGONS.

115. A Polygon is a portion of a plane bounded by straight lines.

The word polygon means many-angled; so that with strict propriety we might limit the definition to plane figures with five or more sides. This limitation in the use of the word is frequently made.

116. A polygon of three sides is a *triangle;* of four, a *quadrilateral;* of five, a *pentagon;* of six, a *hexagon;* of seven, a *heptagon;* of eight, an *octagon;* of nine, a *nonagon;* of ten, a *decagon;* of twelve, a *dodecagon.*

7. Construct a regular octagon.

SUG.—See the general solution (*121*).

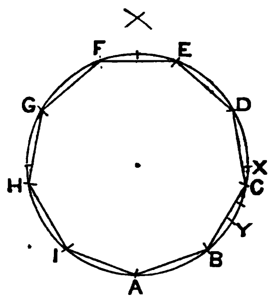

FIG. 100.

8. Construct a regular nonagon.

SOLUTION.—First get a quarter of the circumference by marking the points where two diameters at right angles to each other would cut the circumference. AX is an arc of 90°. Then from A take AY = 60° by using radius as a chord. YX is therefore an arc of 30°. Divide this into three equal parts *by trial*. Measure YB equal to two-thirds of YX, and AB and BC are arcs of 40°, and the chords AB and BC are chords of the regular nonagon.

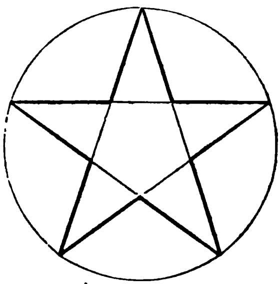

FIG. 101.

9. To draw a five-point star.

SOLUTION.—Draw a circle, and dividing the circumference into five equal parts, join the alternate points of division, as in the figure.

10. To circumscribe a square about a circle (*56*). Also an equilateral triangle, and a regular hexagon.

SYNOPSIS OF PLANE FIGURES.

- PLANE FIGURES.
  - What?
  - CLASSES OF.
    - POLYGONS.
      - What? Sides. Perimeter. Diagonal.
      - TRIANGLES.
        - What? Altitude. Base.
        - Classified by sides.
          - Scalene.
          - Isosceles.
          - Equilateral.
        - Classified by angles.
          - Acute.
          - Right.
          - Obtuse.
      - QUADRILATERALS.
        - What?
        - Trapezium.
        - Trapezoid.
        - Parallelogram.
          - Rhombus.
          - Rhomboid.
          - Rectangular.
            - With unequal sides.
            - Square.
      - Pentagon. Hexagon. Heptagon. Octagon. Nonagon, etc.
        - Regular. What?
    - BOUNDED BY CURVES.
      - CIRCLE.
        - What?
        - Circumference.
        - Centre.
        - Radius, Diameter.
      - CONIC SECTIONS.*
        - Ellipse.
        - Parabola.
        - Hyperbola.
      - HIGHER PLANE CURVES.*

* These are inserted simply to give completeness. Of course, the student is not expected to know more than their names.

PART II.

THE FUNDAMENTAL PROPOSITIONS OF ELEMENTARY GEOMETRY, DEMONSTRATED, ILLUSTRATED, AND APPLIED.

CHAPTER I.

PLANE GEOMETRY.

SECTION I.

OF PERPENDICULAR STRAIGHT LINES.

PROPOSITION I.

***122. Theorem.**—At any point in a straight line, one perpendicular can be erected to the line, and only one, which shall lie on the same side of the line.*

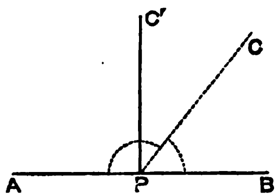

FIG. 102.

DEM.—Let AB* represent any line, and P be any point therein; then, on the same side of AB there can be one and only one perpendicular erected at P. For from P draw any oblique line, as PC, forming with AB the two angles CPB and CPA. Now, while the extremity P, of PC, remains at P, conceive the line PC to revolve so as to increase the less of the two angles, as CPB, and decrease the greater, as CPA. It is evident that for a certain position of CP, as C′P, these

* In class recitation the pupil should go to the blackboard, after having had his proposition assigned him, and first draw the figure required for the demonstration. This should be done neatly, accurately, with dispatch, and *without any aids*. The figure being complete, he stands at the board, pointer in hand, enunciates the proposition, and then gives the demonstration as it is in the text, pointing to the several parts of the figure as they are referred to.

angles will become equal. In this position C'P becomes perpendicular to AB (*26*).* Again, if the line C'P revolve from the position in which the angles are equal, one angle will increase and the other diminish; hence there is *only one* position of the line on this side of AB in which the adjacent angles are equal. Therefore there can be one and only one perpendicular erected to AB at P, which shall lie on the same side of AB. Q. E. D.

123. COR. 1.—*On the other side of the line a second perpendicular, and only one, can be drawn from the same point in the line.*

124. COR. 2.—*If one straight line meets another so as to make the angle on one side of it a right angle, the angle on the other side is also a right angle, and the first line is perpendicular to the second.*

125. COR. 3.—*If two lines intersect so as to make one of the four angles formed a right angle, the other three are right angles, and the lines are mutually perpendicular to each other.*

DEM.—Thus, if CEB is a right angle, CEA, being equal to it, is also a right angle. Then, as AEC is a right angle, the adjacent angle AED is a right angle, since they are equal. Also, as CEB is a right angle, and BED equal to it, BED is a right angle. Hence CD being perpendicular to AB, AB is perpendicular to CD, as it meets CD so as to make the adjacent angles AEC and AED, or CEB and BED equal to each other (*43*).

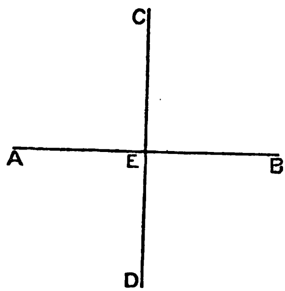

FIG. 103.

PROPOSITION II.

126. Theorem.—*When two straight lines intersect at right angles, if the portion of the plane of the lines on one side of either line be conceived as revolved on that line as an axis until it coincides with the portion of the plane on the other side, the parts of the second line will coincide.*

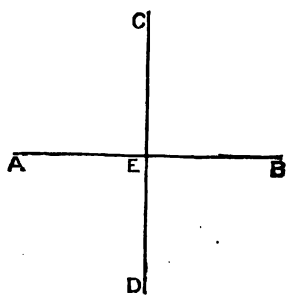

FIG. 104.

DEM.—Let the two lines AB and CD intersect at right angles at E; and let the portion of the plane of the lines on the side of CD on which B lies be conceived to revolve on the line CD as an axis,† until it falls in the

* When a preceding principle is referred to, *it should be accurately quoted by the pupil.*

† As if the paper, which may represent the plane of the lines, were folded in the line CD. It is important that this process be clearly conceived, as it is to be made the basis of many subsequent demonstrations.

portion of the plane on the other side of CD. Then will EB fall in and coincide with AE.

For, the point E being in CD, does not change position in the revolution; and, as EB remains perpendicular to CD, it must coincide with EA after the revolution, or there would be two perpendiculars to CD on the same side and from the same point, E, which is impossible (*122*). Hence EB coincides with EA. Q. E. D.

PROPOSITION III.

127. Theorem.—*From any point without a straight line, one perpendicular can be let fall upon that line, and only one.*

DEM.—Let AB be any line, and P any point without the line; then one perpendicular, and only one, can be let fall from P upon AB.

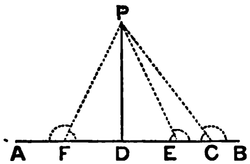

FIG. 105.

For, conceive any oblique line, as PC, drawn, making the angle PCB>PCA. Now, while the extremity P of this line remains fixed, conceive the line to revolve so as to make the greater angle PCB decrease, and the less angle PCA increase. At some position of the revolving line, as PD, the two angles which it makes with the line AB will become equal. When these adjacent angles are equal, the line, as PD, is perpendicular to AB (*26, 43*). Moreover, there is *only one* position of the line in which these angles are equal; hence, only one perpendicular can be drawn from a given point to a given line. Q. E. D.

PROPOSITION IV.

128. Theorem.—*From a point without a straight line, a perpendicular is the shortest distance to the line.*

DEM.—Let AB be any straight line, P any point without it, PD a perpendicular, and PC any oblique line; then is PD<PC.

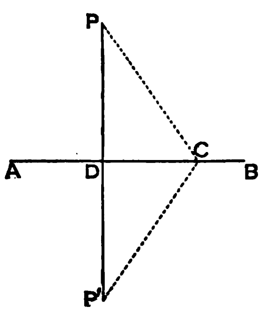

FIG. 106.

Let the portion of the plane of the lines above AB be revolved upon AB as an axis, until it coincides with the portion below AB. Let P' be the point where P falls in the plane below AB. Now conceive the upper part of the plane as revolved back to its original position, and draw PP' and P'C. Again, revolving the upper portion of the plane as before until P falls at P', since the points D and C remain fixed, the lines PD and P'D will coincide, as also the angles PDC and P'DC. Hence, PDC = P'DC, and PD is the perpendicular from P upon AB (*26, 43, 125*). Moreover, PD = P'D and PC = P'C, since they coincide when applied. Finally, PP' being a straight line, is shorter than

PCP′, which is a broken line, since a straight line is the shortest distance between two points. Hence PD, the half of PP′, is less than PC, the half of the broken line PCP′. Q. E. D.

PROPOSITION V.

129. Theorem.—*If a perpendicular be erected at the middle point of a straight line,*

1st. *Any point in the perpendicular is equally distant from the extremities of the line.*

2d. *Any point without the perpendicular is nearer the extremity of the line on its own side of the perpendicular.*

DEM.—1st. Let PD be a perpendicular to AB at its middle point D. Then, O being any point in the perpendicular, OA = OB.

For, revolve the figure OBD upon OD as an axis until it falls in the plane on the other side of PD. Since ODB and ODA are right angles, DB will fall in DA (*126*); and, since DB = DA, B will fall at A. Hence, OA and OB coincide, and OA = OB.

2d. O′ being any point without the perpendicular on the same side as B, O′B < O′A.

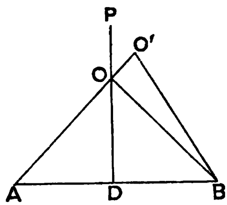

FIG. 107.

For, drawing O′A and O′B, let O be the point at which O′A cuts the perpendicular. Draw OB. Now O′B < BO + OO′, since O′B is a straight and O′OB is a broken line. But, as OA = OB, we may substitute it in the inequality, and have O′B < OA + OO′, which sum = O′A.

130. COR.—*If each of two points in one line is equally distant from the extremities of another line, the former line is perpendicular to the latter at its middle point.*

DEM.—Every point equally distant from the extremities of a straight line lies in a perpendicular to that line at its middle point, by the proposition. But, two points determine the position of a straight line. Hence, two points, each equally distant from the extremities of a straight line, determine the position of the perpendicular at the middle point of the line.

EXERCISES.

1. **Prob.**—*To erect a perpendicular to a given line at a given point in the line.*

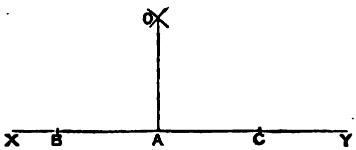

FIG. 108.

SOLUTION.—[The *process* is given in (*44*), and should be repeated here exactly as given there, with the *reasons for the solution*, as follows.] A is one point in the line OA, which is equally distant from B and C, by construction, and O is another. Hence OA is perpendicular to BC at A, by (*130*).

2. ***Prob.***—*To bisect a given line.*

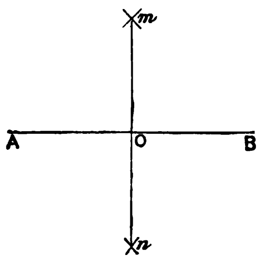

FIG. 109.

SOLUTION.—[For the *process* see (*39*). The student should first do it as he did then. The reason why this process bisects AB is as follows.] Since m is one point equally distant from the extremities A and B, and n another, there are two points in mn each equally distant from the extremities of AB. Hence mn is perpendicular to AB at its middle point O, by (*130*). [The reason for the process in *Fig.* 20 is the same. Let the student give this method, and show how the corollary (*130*) applies.]

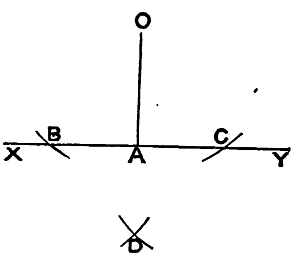

FIG. 110.

3. ***Prob.***—*From a point without a given line, to let fall a perpendicular upon the line.*

SOLUTION.—[Repeat the process as in (*45*), and give the reason for it as follows.] O is one point equally distant from B and C, and D is another. Hence a line drawn from O to D is perpendicular to BC by (*130*).

4. Wishing to erect a line perpendicular to AB at its centre, I take a cord or chain somewhat longer than AB, and, fastening its ends at A and B, take hold of the middle of the cord or chain and carry it as far from AB as I can, first on one side and then on the other, sticking pins at the most remote points, as at P and P′. These points determine the perpendicular sought. What is the principle involved?

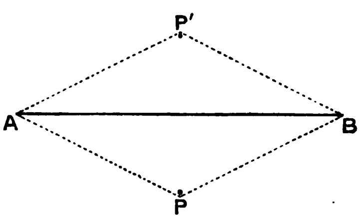

FIG. 111.

5. Two boys are skating together on the ice, and both start from

the same point at the same time, one skating directly to the shore and the other obliquely. They both reach the shore at the same time. Which skates the faster? What principle is involved?

6. Several persons start at different times from the same point in a straight road that runs along a wood, and each travels directly away from the road. Will they come out at the same, or at different points on the opposite side of the wood? What principle is involved? What is the geometrical language for the colloquial phrase "Directly away from the road"?

7. If I go from A to B, *Fig.* 111, by first passing over AP, will I gain or lose in distance by going on a little farther in the direction of AP before I turn and go straight to B? What principle is involved? Would I gain or lose by stopping short of P on the line AP? Why?

SECTION II.

OF OBLIQUE STRAIGHT LINES.

PROPOSITION I.

131. Theorem.—*When an oblique line meets another straight line forming two adjacent angles, the sum of these angles is two right angles.*

DEM.—Let the oblique line CD meet the straight line AB forming the two adjacent angles CDB and CDA; then CDB + CDA equals two right angles.

For suppose CD to revolve toward the position of the perpendicular C′D; the angle CDB will increase at the same rate that CDA diminishes; hence their *sum* will remain constant (*i. e.*, the same). But, when CD becomes perpendicular, the sum of the adjacent angles formed with AB is two right angles by definitions (*26*, *43*). Therefore CDB + CDA = two right angles. Q. E. D.

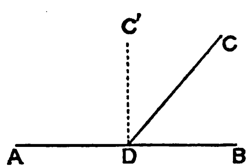

FIG. 112.

132. COR.—*The sum of all the consecutive angles formed by any number of lines meeting a given line on the same side and at a given point is two right angles.*

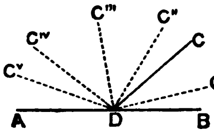

FIG. 113.

DEM.—Thus $ADC^{v} + C^{v}DC^{iv} + C^{iv}DC''' + C'''DC'' + C''DC' + C'DC + CDB = ADC' + C'DB$, which sum is two right angles by the proposition. Or, in general terms, the angles thus formed can always be united into two groups, constituting respectively the two adjacent angles formed by one line meeting another.

133. DEF.—Two angles whose sum is two right angles, are called *Supplemental Angles.* Hence, the *Supplement* of an angle is what remains after subtracting it from two right angles.

PROPOSITION II.

134. Theorem.—*When any two straight lines intersect, the opposite or vertical angles are equal to each other, and the sum of the four angles formed is four right angles.*

DEM.—Let AB and CE intersect at D; then CDA = the opposite angle BDE, ADE = the opposite or vertical angle CDB, and ADC + CDB + BDE + EDA = four right angles. For, since CD meets AB, ADC + CDB = two right angles (*131*). Also, since BD meets CE, CDB + BDE = two right angles. Hence ADC + CDB = CDB + BDE; and, subtracting CDB from both members, there remains ADC = BDE. In a similar manner ADE can be proved equal to CDB. [The student should give the proof.]

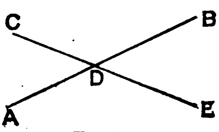

FIG. 114.

Again, since ADC + CDB = two right angles, and BDE + EDA = two right angles, by adding the corresponding members together, we have ADC + CDB + BDE + EDA = four right angles.

135. COR.—*The sum of all the consecutive angles formed by any number of lines meeting at a common point is four right angles.*

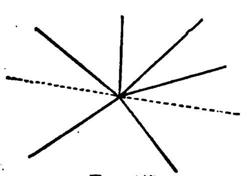
FIG. 115.

DEM.—The truth of this corollary is rendered apparent by drawing a line through the common vertex, and observing that the sum of all the angles on each side thereof is two right angles; whence the sum of all the angles on both sides, which is the same as the sum of all the consecutive angles formed by the line, is four right angles. [Let the student put letters on the figure, and demonstrate by means of it.]

PROPOSITION III.

136. Theorem.—*If two supplemental angles are so situated as to be adjacent to each other, the two sides not common will fall in the same straight line.*

DEM.—Let the sum of the two angles BOA and CO'D be two right angles. Prolong CO', forming the angle DO'E. Then is DO'E supplemental to CO'D (***131, 133***), and hence equal to BOA, which is supplemental to CO'D by hypothesis. Now, if AOB be placed adjacent to CO'D, the vertex O being at O', and the side OA falling in O'D, OB will fall in O'E, since BOA = DO'E. Hence, when the angles are so situated, OB becomes the prolongation of CO'. Q. E. D.

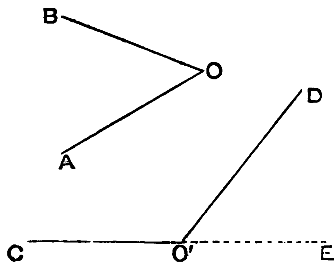

FIG. 116.

PROPOSITION IV.

137. Theorem.—*If from a point without a straight line a perpendicular be drawn, oblique lines from the same point cutting the line at equal distances from the foot of the perpendicular are equal to each other; the angles which they form with the perpendicular are equal to each other; and the angles which they form with the line are equal to each other.*

DEM.—Let AB be any straight line, P any point without it, PD a perpendicular, and PC and PE oblique lines cutting AB at C and E, so that DC=DE; then PC=PE, angle CPD = angle DPE, and angle PCD = angle PED.

Revolve the figure PDE upon PD as an axis, until it falls in the plane on the other side of PD. Since AB is perpendicular to PD, DB will fall in DA; and, since DE = DC, E will fall at C. Now, as P remains stationary, the triangles PDE and PDC coincide. Hence, PC = PE, angle CPD = angle DPE, and angle PCD = angle PED. Q. E. D.

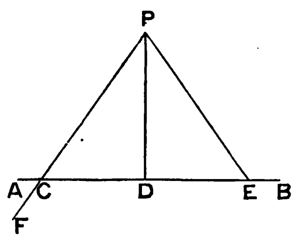

FIG. 117.

QUERY.—How does the equality of PE and PC follow from (***129***).

PROPOSITION V.

138. Theorem.—*If from a point without a line a perpendicular be drawn to the line, and also from the same point two oblique*

*lines making equal angles with the perpendicular, the oblique lines are equal to each other, cut the line at equal distances from the foot of the perpendicular, and make equal angles with it.**

DEM.—PD being a perpendicular to AB, and angle CPD equal to angle DPE, PC equals PE, CD equals DE, and PCD equals PED.

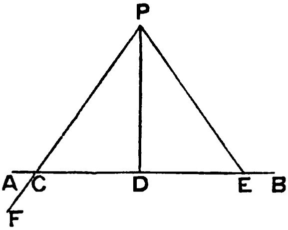

FIG. 118.

Revolve the figure PDE upon PD as an axis, till it falls in the plane of PDC. Since angle EPD = angle CPD, PE will take the direction PC, and E will fall somewhere in the indefinite line PF. But, since PDE and PDC are right angles, DE will fall in DA (*126*) and E will fall somewhere in the indefinite line DA. Now, as E falls at the same time in PF and DA, it must fall at their intersection C. Hence, PE coincides with PC, and DE with DC. Therefore PE = PC, DE = DC, and angle PED = PCD. Q. E. D.

PROPOSITION VI.

***139. Theorem.**—If from a point without a line a perpendicular be let fall on the line, and two oblique lines be drawn, the oblique line which cuts off the greater distance from the foot of the perpendicular is the greater.*

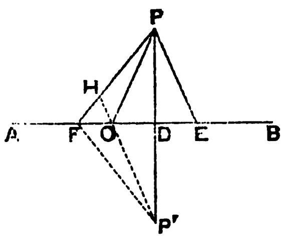

FIG. 119.

DEM.—Let AB be any straight line, P any point without it, and PO and PF two oblique lines of which PF cuts off the greater distance from the foot of the perpendicular; that is DF > DO. Then is PF > PO.

Revolve the figure FPD upon AB as an axis, until it falls in the plane on the opposite side of AB. Let P′ be the point at which P falls; and revolve the figure FPD back to its original position. Draw P′D, P′F, and P′O producing the latter till it meets PF in H. Then P′D = PD, P′O = PO, and P′F = PF. Now the broken line POP′ < than the broken line PHP′, since the straight line PO < the broken line PHO. For a like reason the broken line PHP′ < PFP′, since HP′ < HFP′. Hence POP′ < PFP′, and PO the half of POP′ < PF the half of PFP′. Q. E. D.

SCH.—If the two oblique lines to be compared lie on different sides of the perpendicular, as PF and PE, DF being greater than DE, lay off DC = DE, and draw PC. Then since PC = PE, if it is found less than PF, as in the demonstration, PE is less than PF.

* This proposition is the *converse* of the last. The significance of this statement will be more fully developed farther on (*154*).

140. COR. 1.—*From a given point without a line, there can not be two equal oblique lines drawn to the line on the same side of a perpendicular from the point to the line.*

141. COR. 2.—*Two equal oblique lines drawn from the same point in a perpendicular to a given line, cut off equal distances on that line from the foot of the perpendicular.*

DEM.—For, if the distances cut off were unequal, the lines would be unequal.

EXERCISES.

1. Having an angle given, how can you construct its supplement? Draw any angle on the blackboard, and then construct its supplement.

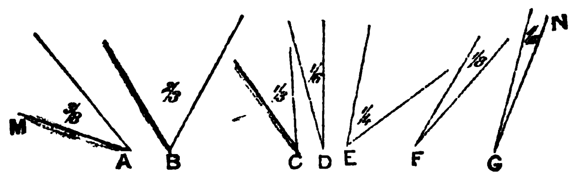

FIG. 120.

2. The several angles in the figure are such parts of a rignt angle as are indicated by the fractions placed in them. If these angles are added together by bringing the vertices together and causing the adjacent sides of the angles to coincide, how will MA and GN lie? Construct seven consecutive angles of these several magnitudes. How do the two sides not common lie? Why?

3. If two times A, B, two times D, three times E, three times C, three times G, two times F, in the last figure, are added in order, how will AM and GN lie with reference to each other? Why?

Ans. They will coincide.

4. If you place the vertices of any two equal angles together so that two of the sides shall extend in opposite directions and form one and the same straight line, the other two sides lying on opposite sides thereof, how will the latter sides lie? By what principle?

5. Upon what principle in this section may the common method of erecting a perpendicular at the middle of a straight line (***39, 44***) be explained? Upon what the method of letting fall a perpendicular upon a straight line from a point without (***45***)?

6. A and B start at the same time, from the same point in a certain road; A travels directly to a point in another road at right angles to the first, and at ten miles from their intersection, and B travels directly toward a second point in the second road, which point is seven miles from the intersection. Both reach their destination at the same time. Which travels the faster? What principle is involved?

SECTION III.

OF PARALLELS.

PROPOSITION I.

142. Theorem.—*Two straight lines lying in the same plane and perpendicular to a third line are parallel to each other.*

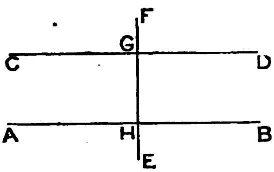

FIG. 121.

DEM.—Let AB and CD be two straight lines lying in the same plane and each perpendicular to FE; then are they parallel.

For if AB and CD are not parallel, they will meet at some point if sufficiently produced (*66*). But, if they could meet, we should have two straight lines from one point (their point of meeting), perpendicular to the same straight line, which is impossible (*127*). Therefore, as the lines lie in the same plane and cannot meet how far soever they be produced, they are parallel. Q. E. D.

143. COR. 1.—*Through the same point one parallel can always be drawn to a given line, and only one.*

DEM.—Let AB be the given line, and C the given point, there can be one and only one perpendicular through C to AB (*127*.) Let this be FE. Now through C one and only one perpendicular can be drawn to FE. Let this be CD. Then is CD parallel to AB by the proposition. That there is only one such parallel, we shall assume as axiomatic.*

144. COR. 2.—*If a straight line is perpendicular to one of two parallels, it is perpendicular to the other also.*

DEM.—If FE is perpendicular to AB it is perpendicular to CD. For, if through C where FE intersects CD, a perpendicular be drawn to FE, it is par-

* Nous regarderons cette proposition comme ÉVIDENTE. P.-F. COMPAGNON. So also CHAUVENET.

allel to AB by the proposition. But, by *Cor.* 1, there can be but one line through C parallel to AB. Hence the perpendicular to FE at C coincides with, or is, the parallel CD.

PROPOSITION II.

145. Theorem.—*Two straight lines which are parallel to a third, are parallel to each other.*

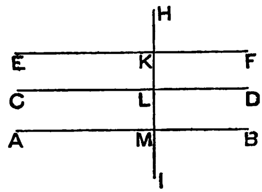

Fig. 122.

Dem.—Let AB and CD be each parallel to EF; then are they parallel to each other.

For draw HI perpendicular to EF; then will it be perpendicular to CD because CD is parallel to EF. For a like reason HI is perpendicular to AB. Hence CD and AB are both perpendicular to HI, and consequently parallel. Q. E. D.

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146. Definitions.—When two lines are cut by a third line the angles formed are named as follows:

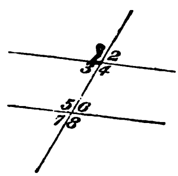

Fig. 123.

Exterior Angles are those without the two lines, as 1, 2, 7, and 8.

Interior Angles are those within the two lines, as 3, 4, 5, and 6.

Alternate Exterior Angles are those without the two lines and on different sides of the secant line, but not adjacent, as 2 and 7, 1 and 8.

Alternate Interior Angles are those within the two lines and on different sides of the secant line but not adjacent, as 3 and 6, 4 and 5.

Corresponding Angles are one without and one within the two lines, and on the same side of the secant line but not adjacent, as 2 and 6, 4 and 8, 1 and 5, 3 and 7.

PROPOSITION III.

147. Theorem.—*If two lines are cut by a third line, making the sum of the interior angles on the same side of the secant line equal to two right angles, the two lines are parallel.*

Dem.—Let AB and CD be met by the line EF, making ECD + FKB = two right angles; then are AB and CD parallel.

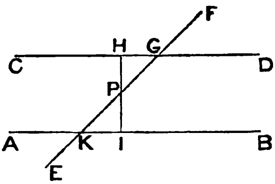

Fig. 124.

For, through P, the middle of GK, draw HI perpendicular to AB. Since HPG and KPI are vertical angles, they are equal by (*134*). Also, since GKB and CGK are both supplements of DGK, the former by hypothesis, and the latter by (*133*), GKB = CGK. Now, conceive the portion of the figure below P, while remaining in the same plane (the plane of the paper), to revolve upon P (as a pivot) from right to left till PK falls in PG.* Since PK = PG, K will fall at G. Again, since KPI = GPH PI will take the direction PH, and I will fall in PH, or PH produced; and, since PKI = PGH, KI will take the direction GH, and I will fall somewhere in GC. Hence, as I falls in both PH and GC, it must fall at their intersection H; and KIP coincides with, and is equal to PHG. But KIP is a right angle by construction; hence GHP is a right angle. Therefore, AB and CD are both perpendicular to HI, and consequently parallel by (*142*). Q. E. D.

148. Cor. 1.—*If two lines are cut by a third, making the sum of the two exterior angles on the same side of the secant line equal to two right angles, the two lines are parallel.*

Dem.—For, if FGD + EKB = two right angles, EKB must = KGD, since FGD + KGD = two right angles. Also, if FGD + EKB = two right angles, FGD must = GKB, since GKB + EKB = two right angles. Hence, when FGD + EKB = two right angles, GKB + KGD = two right angles, and the lines are parallel by the proposition. The same is true for FGC and AKE. [Let the student prove it.]

149. Cor. 2.—*If two lines are cut by a third, making either two alternate interior, or either two alternate exterior, or either two corresponding angles, equal to each other, the lines are parallel.*

Dem.—If CGK = GKB, KGD + GKB = two right angles, since CGK + KGD = two right angles. Hence the lines are parallel by the proposition. So also if KGD = AKG, or FGD = AKE, or CGF = EKB, or FGD = GKB, or CGF = AKG, the two lines are parallel. [Let the student show the truth in each case.]

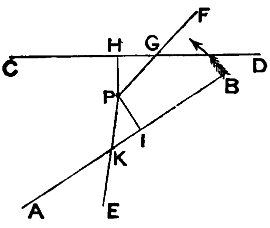

Fig. 125.

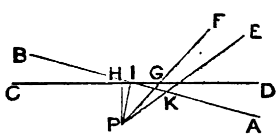

Fig. 126.

* The accompanying figures will aid the student in getting this conception. *Fig.* 125 represents the position of the lines after the revolution has gone about half a right angle, and *Fig.* 126 when the revolution is almost completed.

PROPOSITION IV.

150. Theorem.—*If two parallel lines are cut by a third line, the sum of the interior angles on the same side of the secant line is equal to two right angles.*

DEM.—Let the parallels AB and CD be cut by EF, then is DCK + CKB = two right angles.

For, if DCK is not the supplement of CKB, let LM be drawn through C so as to make MCK that supplement. Then, by the preceding proposition, LM is parallel to AB; and we have two parallels to AB through the point C, which is impossible (*143*). Hence, as no line but a parallel can make this interior angle the supplement of the other, the parallel makes it so. Q. E. D.

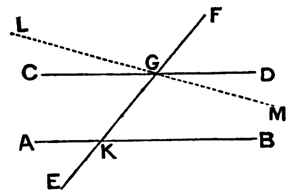

FIG. 127.

[Let the student demonstrate this proposition as the preceding was demonstrated. In this case CD and AB are parallel by hypothesis, and HI being drawn perpendicular to one is perpendicular to the other also. When K falls at C, KI falls on CC, since from a point without a line only one perpendicular can be drawn to that line.]

151. COR. 1.—*If two parallel lines are cut by a third line, the sum of either two exterior angles on the same side of the secant line is equal to two right angles.*

DEM.—FCD + EKB = two right angles. For FCD + DCK = two right angles, and DCK + CKB = two right angles; whence FCD = CKB. In like manner, CKB + EKB = two right angles; and DCK + CKB = two right angles; whence EKB = DCK. Therefore, FCD + EKB = CKB + DCK = two right angles, by the proposition.

152. COR. 2.—*If two parallel lines are cut by a third line, either two alternate interior, or either two alternate exterior, or either two corresponding angles, are equal to each other.*

DEM.—If CD and AB are parallel, CCK = CKB. For CCK + DCK = DCK + CKB, the former being equal to two right angles by (*131*), and the latter by this proposition. Hence, subtracting DCK from both members, CCK = CKB. [Let the student show in like manner that AKC = KCD, FCD = AKE, CCF = EKB, FCD = CKB, and CCF = AKC.]

153. COR. 3.—*Of the eight angles formed when one line cuts two parallels, the four acute angles are equal each to each, and the four obtuse angles; or, in case any one angle is a right angle, all the others are right angles.*

154. SCH.—The last two propositions and their corollaries are the *converse* of each other; *i. e.*, the hypotheses or data and the conclusions or things proved are exchanged. Thus, in PROP. III., the hypothesis is, that *The sum of the two interior angles on the same side of the secant line is equal to two right angles;* and the conclusion is, that *The two lines are parallel.* Now, in PROP. IV., the hypothesis is, that *The two lines are parallel;* and the conclusion is, that *The sum of the two interior angles on the same side of the secant line is two right angles.** [A clear conception of this scholium will save the student from confounding these propositions.]

PROPOSITION V.

155. Theorem.—*If two straight lines are cut by a third line making the sum of the interior angles on one side of the secant line less than two right angles, the two lines will meet on this side of the secant line, if sufficiently produced.*

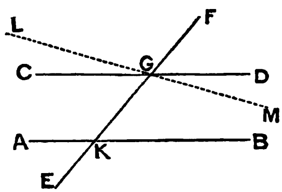

FIG. 128.

DEM.—Let AB and LM be cut by EF making MGK + FKB < two right angles; then will AB and LM meet on the side of EF on which MGK and FKB lie, if sufficiently produced.

For the angle which a parallel to AB through G makes with EF is the supplement of FKB. But by hypothesis MGK is less than this supplement. Hence the portion GM, of the line LM, lies within GD, and will meet KB if sufficiently produced. Q. E. D.

PROPOSITION VI.

156. Theorem.—*Two parallels are everywhere equally distant from each other.*

DEM.—Let E and F be any two points in the line CD, and EG and FH perpendiculars measuring the distances between the parallels CD and AB at these points; then is EG = FH.

For, let P be the middle point between E and F, and PO a perpendicular at

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* The learner may think that, if a proposition is true, its converse is necessarily true; and hence, that when a proposition has been proved, its converse may be assumed as also proved. Now this is by no means always the case. Although in a great variety of mathematical propositions, it happens that the proposition and its converse *are* both true, we never assume one from having proved the other; and we shall occasionally find a proposition whose converse is not true.

this point. Revolve the portion of the figure on the right of PO, upon PO as an axis, until it falls upon the plane of the paper at the left. Then, since FPO and EPO are right angles, PD will fall in PC; and, as PF = PE, F will fall on E. As F and E are right angles, FH will take the direction EG, and H will lie in EG or EG produced. Also,

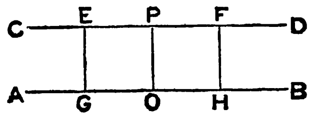

FIG. 129.

as POH and POG are right angles, OB will fall in OA, and H falling at the same time in EG and OA is at their intersection G. Hence FH coincides with and is equal to EG. Q. E. D.

EXERCISES.

1. ***Prob.***—*Through a given point to draw a line parallel to a given line, by the principle contained in* PROP. I. *of this section.*

SUG'S.—Draw a straight line on the blackboard. Designate with a dot some point without the line. To draw a line through the designated point and parallel to the given line, is the problem. Let fall a perpendicular upon the line from the point. Then through the given point draw a line perpendicular to this perpendicular. The latter line will be parallel to the given line. (By what proposition?)

2. ***Prob.***—*Through a given point to draw a parallel to a given line by* PROP. III.

SUG'S.—Through the given point draw an oblique line cutting the given line. Then draw a line through the given point making an angle with the oblique line equal to the supplement of the angle which is included between the oblique line and the given line, and on the same side of the former. [Of course the student will be required to *do the work on* the blackboard, *guessing at nothing.*]

3. ***Prob.***—*Through a given point to draw a line parallel to a given line, upon the principle that the alternate angles made by a secant line are equal* (***152***).

4. A *bevel* is an instrument much used by carpenters, and consists of a main limb AB, in which a tongue CD is placed, so as to open and shut like the blade of a knife. This tongue turns on the pivot O, which is a screw, and can be tightened so as to hold the tongue firmly at any angle with the limb. The tongue can also be adjusted so as

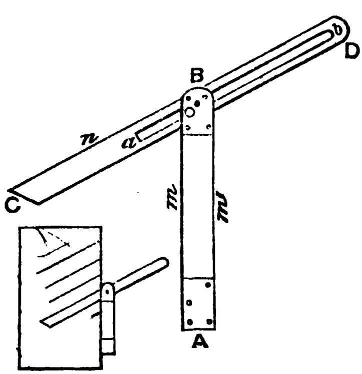

FIG. 130.

to allow a greater or less portion to extend on a given side, as CB, of the limb. Now, suppose the tongue fixed in position, as represented in the figure, and the side *m* of the limb to be placed against the straight edge of a board, and slid up and down, while lines are drawn along the side *n* of the tongue. What will be the relative position of these lines? Upon what proposition does their relative position depend? How can the carpenter adjust the bevel to a right angle upon the principle in Prop. I., Sec. 1? At what angle is the bevel set, when, drawing two lines from the same point in the edge of the board, one with one edge *m* of the bevel against the edge of the board, and the other with the other edge m', these lines are at right angles to each other?

5. Are the two walls of a building which are carried up by the plumb line exactly parallel? Why?

6. Pass a circumference through three given points, as in (*58*), and show from principles contained in one of the preceding sections, that O is equally distant from A, B, and C; and hence that, if a circumference be drawn from O as a centre with a radius OA, it will pass through A, B, and C.

7. Construct two triangles of unequal sizes, but having the sides of the one respectively parallel to the sides of the other. Are they shaped alike?

8. Construct two triangles of unequal sizes, but having the sides of the one respectively perpendicular to the sides of the other. Are they shaped alike?

9. Construct a parallelogram, two of whose sides are 6 and 10. Can you construct different-shaped figures with the same sides?

SYNOPSIS OF THE THREE PRECEDING SECTIONS.

RELATIVE POSITIONS OF STRAIGHT LINES.

- **PERPENDICULARS.**
  - Definition (*43*).
  - PROP. I. One and only one to a given line at a given point.
    - *Cor.* 1. Second perp.
    - *Cor.* 2. If one angle is right.
    - *Cor.* 3. One of 4 angles right.
  - PROP. II. Revolved perpendicular.
  - PROP. III. From a point without a line.
  - PROP. IV. Shortest distance from a point to a line.
  - PROP. V. Point in. Without.
    - *Cor.* Two points equally distant from extremities of a line.
  - EXERCISES.
    - *Prob.* To erect a perpendicular.
    - *Prob.* To bisect a line.
    - *Prob.* To let fall a perpendicular.
    - Other exercises.
- **OBLIQUE LINES.**
  - PROP. I. Sum of adjacent angles.
    - *Cor.* Sum of consec. angles on one side of line.
    - *Def.* Supplement.
  - PROP. II. Opp. angles equal.
    - *Cor.* Angles about a point.
  - PROP. III. Supplemental angles made adjacent.
  - PROP. IV. Cutting equal distances from foot of perpendicular.
  - PROP. V. Making equal angles with perpendicular.
  - PROP. VI. Cutting unequal distances from the foot of perpendicular.
    - *Cor.* 1. Not two equal on same side of perpendic.
    - *Cor.* 2. Two equal oblique lines.
  - EXERCISES.
- **PARALLELS.**
  - Definition (*66*).
  - PROP. I. Two perpendiculars to a line.
    - *Cor.* 1. One parallel through a point.
    - *Cor.* 2. A perp. to one of two parallels.
  - PROP. II. Two lines parallel to a third.
  - A SECANT TO.
    - Def's of angles formed.
      - Exterior, Interior, Alternate Exterior, Alternate Interior, Corresponding.
    - PROP. III. Sum of Inter. angles, two right angles.
      - *Cor.* 1. Sum of two Exterior angles, two right angles.
      - *Cor.* 2. Two Alt. Inter., Alt. Exter., or Correspond'g angles equal.
    - PROP. IV. Converse of III.
      - *Cor.* 1. Converse of Cor. 1., Prop. III.
      - *Cor.* 2. Converse of Cor. 2., Prop. III.
      - *Cor.* 3. Of the eight angles.
      - *Sch.* Meaning of Converse.
    - PROP. V. Sum of Inter. angles < 2 right angles.
  - PROP. VI. Everywhere equidistant.
  - EXERCISES.—*Probs.* 1, 2, 3. Methods of drawing.

SECTION IV.

OF THE RELATIVE POSITIONS OF STRAIGHT LINES AND CIRCUMFERENCES.

PROPOSITION I.

158. Theorem.—*Any diameter divides a circle, and also its circumference, into two equal parts.*

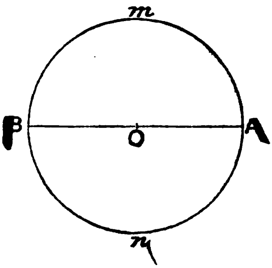

FIG. 131.

DEM.—Let AB be any diameter of the circle $AmBn$; then is the figure AmB equal to AnB.

For revolve AnB upon AB as an axis until it falls on the plane of AmB. Then, since every point in AnB is at the same distance from the centre O, as every point in AmB, the figures will coincide, and are, consequently, equal. Hence surface AnB = surface AmB, and arc AnB = arc AmB. Q. E. D.

PROPOSITION II.

159. Theorem.—*A radius which is perpendicular to a chord bisects the chord and also the subtended arc.*

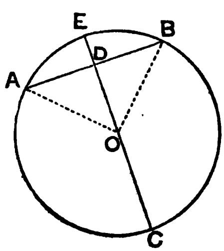

FIG. 132.

DEM.—Let AB be any chord and OE a radius perpendicular to it at D; then AD = BD, and AE = BE.*

For, drawing the radii OA and OB, revolve the semicircle CBE upon the diameter CE until it falls on CAE. The semicircles will coincide (*158*); and since AB is perpendicular to OE, DB will fall in DA. Moreover, as there cannot be two equal oblique lines from a point to a line on the same side of a perpendicular, OB and OA must coincide. Hence BD coincides with AD, and BE with AE. Therefore AD = BD, and AE = BE. Q. E. D.

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* To avoid confusing the pupil by a multiplicity of details, the demonstrations in this section are generally limited to the consideration of arcs less than a semi-circumference. All the propositions, except PROP. V., are equally true whatever the arcs, and the demonstrations can easily be applied to cases in which the arcs are greater than semi-circumferences. But this had better not be done till a review is taken, for the reason given above.

160. Cor. 1.—*A radius which is perpendicular to a chord bisects the angle subtended by the arc of that chord.*

Thus OE bisects AOB, since BOE is found to coincide with AOE in the demonstration above.

161. Cor. 2.—Conversely, *A radius which bisects an arc is perpendicular to the chord of that arc at its middle point.*

Dem.—If OE bisects arc AB at E, when semicircle CBE is revolved on CE till it falls on CAE, EB will coincide with EA; and as D remains fixed and B falls on A, BD coincides with DA. Hence OE has two points, O and D, each equidistant from the extremities of AB, and is, consequently, perpendicular to it at its middle point.

162. Cor. 3.—Also, conversely, *A radius which bisects a chord is perpendicular to the chord and bisects the subtended arc.*

For it has two points, each equidistant from the extremities of the chord.

163. Cor. 4.—*The line* OD *measures the distance of the chord* AB *from the centre;* since by the distance from a point to a line is always meant the *shortest* distance.

PROPOSITION III.

164. Theorem.—*In the same or in equal circles, equal chords are equally distant from the centre.*

Dem.—Let O and O′ be two equal circles, and chord EF = chord GH; then are the perpendiculars LO and NO′, which measure the distances of the chords from the centre (*163*), equal.

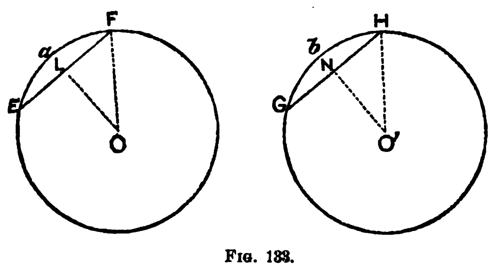

Fig. 133.

For, since FE is perpendicular to LO and GH to NO′, and LF = NH (*159*), the equal oblique lines FO and HO′ cut off equal distances from the foot of each perpendicular (*141*). Therefore LO = NO′. Q. E. D.

PROPOSITION IV.

165. Theorem.—*In the same or in equal circles, equal arcs have equal chords; and conversely, equal chords subtend equal arcs.*

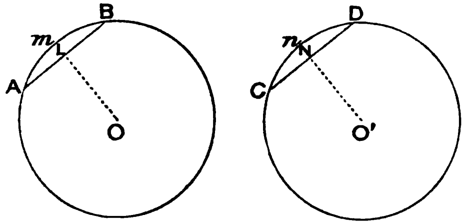

FIG. 134.

DEM.—Let O and O′ be the centres of two equal circles, and arc A*m*B = arc C*n*D; then chord AB = chord CD.

Apply the circle O′ to the circle O, with O′ at O, and C at A. Since the circumferences coincide, all the points in each being equally distant from the centre, and since arc A*m*B = arc C*n*D by hypothesis, D will fall at B. Hence AB = CD.

Conversely, if chord AB = chord CD, arc A*m*B = arc C*n*D. Draw the perpendiculars OL and O′N from the centres to the chords. Conceive the plane of circle O′ placed upon circle O, so that CD shall fall upon its equal AB, and O′ be on the same side of AB as O. Since L and N are the middle points of the equal chords, they will coincide; and as LO and NO′ are perpendiculars to the respective chords, and equal (*164*), O′ will fall at O. As the circles are equal, the circumferences will coincide, and consequently the arc A*m*B coincides with C*n*D.

PROPOSITION V.

166. Theorem.—*In the same or in equal circles, the less of two arcs has the shorter chord; and, conversely, the shorter chord subtends the less arc.*

DEM.—Let O and O′ be the centres of two equal circles, and arc A*m*B be less than arc C*n*D; then is chord AB < chord CD.

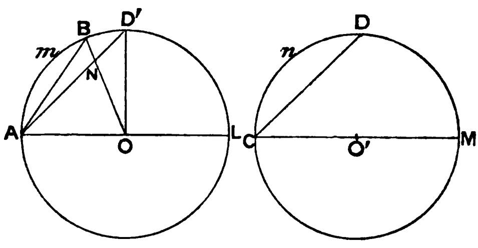

FIG. 135.

Drawing the diameters AL and CM, place circle O′ upon circle O, with CM upon AL. Take arc AD′ = arc C*n*D and draw AD′, OB, and OD′. AD′ = CD by (*165*). Now AB $\nless$ AN + NB. Also OD′ < ND′ + NO; or, as OD′ = OB, OB < ND′ + NO. Subtracting NO from both members, OB − NO (or NB) < ND′. Hence, we may substitute ND′ for NB in the inequality AB < AN + NB and have AB < AN + ND′ or AD′, which equals CD.

Conversely, if chord AB is less than chord CD, arc AmB is less than arc CnD. For if arc AmB = arc CnD, chord AB = chord CD (*165*). And, if arc AmB > arc CnD, chord AB > chord CD. But both of these conclusions are contrary to the hypothesis. Hence, as arc AmB can neither be equal to nor greater than arc CnD, it must be less.

PROPOSITION VI.

167. Theorem.—*In the same or in equal circles, of two unequal chords, the less is at the greater distance from the centre.*

DEM.—Let CE < AB, then is the perpendicular OD, which measures the distance of CE from the centre, greater than OD′ which measures the distance of AB from the centre.

From A lay off AE′ = CE, and draw the perpendicular OD″. Then OD″ = OD, since equal chords are equally distant from the centre. As arc AE′ < arc AB, AB cuts OD″ in some point as H. Now OH > OD′ since the former is oblique and the latter perpendicular to AB. Also OD″ > OH. Much more then is OD″ > OD′. Therefore OD (which equals OD″) > OD′. Q. E. D.

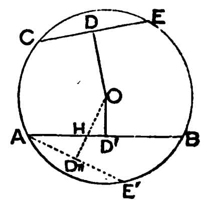

FIG. 136.

168. COR.—Conversely, *Of two chords which are unequally distant from the centre, that which is at the greater distance is the less.*

DEM.—Thus, if CE is at a greater distance from the centre than AB, CE < AB. For, if CE were equal to AB, it would be equally distant from the centre. And if CE were greater than AB, it would be at a less distance from the centre. Hence, as CE cannot be at an *equal* distance from the centre with AB, nor at a *less* distance, it must be at a greater.

PROPOSITION VII.

169. Theorem.—*A straight line can intersect a circumference in only two points.*

DEM.—The distances from the centre to the intersections, being radii, are equal. Hence, as there can be only two equal straight lines drawn from a point to a straight line, there can be only two intersections. Q. E. D.

PROPOSITION VIII.

170. Theorem.—*A straight line which intersects a circumference in one point intersects it also in a second point.*

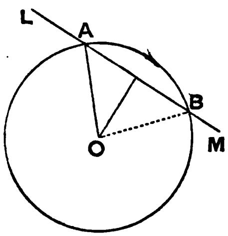

FIG. 137.

DEM.—Let LM intersect the circumference at A; then does it intersect at some other point, as B.

For, since LM intersects the circumference, it passes within it, and has points nearer to O than A. The radius OA is, therefore, an oblique line. Now two equal oblique lines can be drawn from O to the straight line LM. But all points in the plane at the distance OA from O, are in the circumference. Hence there is a second point, as B, common to LM and the circumference. Q. E. D.

171. COR.—*Any line which is oblique to a radius at its extremity, is a secant line.*

PROPOSITION IX.

172. Theorem.—*A straight line which is perpendicular to a radius at its extremity is tangent to the circumference.*

DEM.—The line touches the circumference because the extremity of the radius is in the circumference. Moreover, it does not intersect the circumference, since, if it did, it would have points nearer the centre than the extremity of the radius; but these it cannot have, as the perpendicular is the shortest distance from a point to a line. Hence, as a line which is perpendicular to a radius at its extremity touches the circumference but does not intersect it, it is a tangent (*53*). Q. E. D.

173. COR.—Conversely, *A tangent to a circumference is perpendicular to a radius at the point of contact.*

For, as a tangent to a circumference does not pass within, the point of contact is the nearest point to the centre, and hence is the foot of a perpendicular from the centre.

PROPOSITION X.

174. Theorem.—*Two parallel secants intercept equal arcs.*

DEM.—Let the parallels LM and RS intersect the circumference AECF; then are the intercepted arcs AB and DC equal.

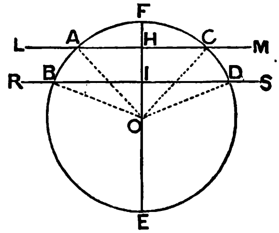

FIG. 138.

Draw the diameter EF perpendicular to one of the parallels, as LM, whence it will be perpendicular to the other (*144*). Draw the radii OB and OD. Revolve the portion of the figure on the right of EF, upon EF until it falls on the plane on the left of EF. Then, since RS and LM are perpendicular to EF, IS will fall in IR, and HM in HL. Moreover, as there cannot be two equal oblique lines on the same side of a perpendicular, and from the same point (*140*), OD and OB must coincide, and D fall at B. In like manner C falls at A, and CD coincides with AB. Therefore CD = AB. Q. E. D.

PROPOSITION XI.

175. Theorem.—*If a secant be parallel to a tangent, the arcs intercepted between the intersections and the point of tangency are equal.*

DEM.—Let the secant LM be parallel to the tangent RS; then is CP = EP.

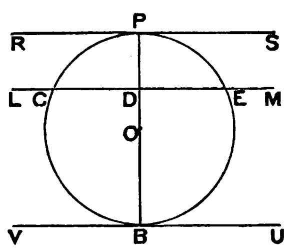

FIG. 139.

For, draw the radius OP to the point of tangency; it will be perpendicular to the tangent (*173*), and also to the parallel LM (*144*). But a radius which is perpendicular to a chord, as OP to CE, bisects the subtended arc (*159*), hence CP = EP. In like manner, if VU is parallel to LM, CB = EB. Q. E. D.

176. COR.—*Two parallel tangents include equal arcs between the points of tangency; and these arcs are semi-circumferences.*

EXERCISES.

1. Draw a circle and divide it into two equal parts. What proposition is involved?

2. Given a point in a circumference, to find where a semi-circumference reckoned from this point terminates. What proposition is involved?

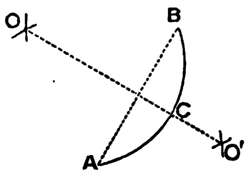

FIG. 140.

3. ***Prob.***—*To bisect a given arc.*

SOLUTION.—Let AB be an arc which we wish to bisect.* Draw its chord AB, and erect OO′ bisecting the chord, by (*130*). Now, as OO′ is perpendicular to the chord at its middle point, it bisects the arc by (*162*), since there can be but one perpendicular at the middle point of the chord. The arc AB is, therefore, bisected at C, *i.e.*, AC = CB.

4. ***Prob.***—*To bisect a given angle.*

SUG.—The method of solving this is given in PART I. The student should *do it* as there directed, and then point out the principle upon which the method depends.

5. In a circle whose radius is 11 there are drawn two chords, one at 6 from the centre, and one at 4. Which chord is the greater? By what proposition?

6. In a certain circle there are two chords, each 15 inches in length. What are their relative distances from the centre? Quote the principle.

7. There is a circular plat of ground whose diameter is 20 rods. A straight path in passing runs within 7 rods of the centre. What is the position of the path with reference to the plat?* What is the position of a straight path whose nearest point is 10 rods from the centre? One whose nearest point is 11 rods from the centre?

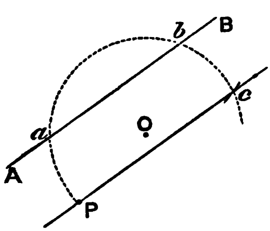

FIG. 141.

8. Pass a line through a given point, and parallel to a given line, by the principles contained in (*174*) and (*165*).

* This solution and many others are given, not so much that it is feared that the student will not be able to solve the problems, as to afford models for describing the process. In this case an arc should be drawn first, and all trace of the centre obliterated. *Then* proceed as directed.

9. ***Prob.**—To draw a tangent to a circle at a given point in the circumference.*

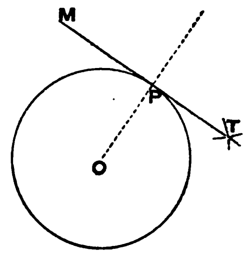

FIG. 141*.

SOLUTION.—Let **P** be the point at which a tangent is to be drawn. Draw the radius **OP** to the given point of tangency, and produce it any convenient distance beyond the circle. Erect a perpendicular to this line at **P**, as **MT**; then is **MT** a tangent to the circle (*172*).

10. ***Prob.**—To find the centre of a circle whose circumference is known, or of any arc of it.*

SUG.—The *process* is given in PART I. Do the work as there directed, and then show upon what proposition in this section it is founded.

SYNOPSIS.

RELATIVE POSITIONS OF STRAIGHT LINES AND CIRCUMFERENCES.

DIAMETERS.	PROP. I. How divide circles and circumferences.	
CHORDS.	PROP. II. Radius perp. to chord.	*Cor.* 1. Bisects angle. *Cor.* 2. Converse of Cor. 1. *Cor.* 3. " " " *Cor.* 4. Dist. from centre.
	PROP. III. Distance of equal chords from centre.	
	PROP. IV. Equal arcs, and converse.	
	PROP. V. Unequal arcs.	
	PROP. VI. Unequal chords. Distance from centre.	*Cor.* Converse.
SECANTS.	PROP. VII. Intersect in only two points.	
	PROP. VIII. If a line intersect in one point, it intersects also in another.	*Cor.* Line oblique to radius at extr.
TANGENTS.	PROP. IX. Line perpendicular to radius at extremity.	*Cor.* Converse.
PARALLELS.	PROP. X. Parallel secants intercept equal arcs.	
	PROP. XI. Secant par. to tangent.	*Cor.* Two parallel tangents.
EXERCISES.	*Prob.* To bisect an arc.	
	Prob. To bisect an angle.	
	Prob. To draw a tangent at a point in circumference.	
	Prob. To find centre of circumference or arc.	

SECTION V.

OF THE RELATIVE POSITIONS OF CIRCUMFERENCES.

PROPOSITION I.

177. Theorem.*—All the circumferences which may be passed through three points not in the same straight line coincide, and are one and the same.*

DEM.—Let A, B, and C be three points not in the same straight line; then all the circumferences which can be passed through them will coincide.

For join the points, two and two, by straight lines, as AB and BC. Bisect these lines with perpendiculars, as DF and EH. Since AB and BC are not in the same straight line, DF and EH will meet when sufficiently produced, at one and only one point, as O, because they are straight lines Now, every point in FD is equally distant from A and B, and every point in HE is equally distant from B and C (*129*). Hence O is equally distant from the three points A, B, and C; and, if a circumference be drawn with O as a centre, and a radius AO, it will pass through the three points. Moreover, every circumference passing through these points must have O for its centre, since the centre must be in FD (otherwise it would be unequally distant from A and B), and also in HE (*129*). But these lines intersect only in O. Also, every circumference with O as its centre, and passing through A, must have AO for its radius. Hence, as all circles having the same centre and the same radius coincide, all those passing through three points, A, B, and C, coincide. Q. E. D.

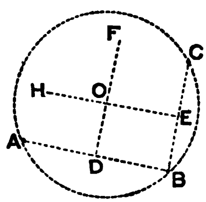

FIG. 142.

178. COR. 1.—*Through any three points not in the same straight line a circumference can be passed.*

179. COR. 2.—*Three points not in the same straight line determine a circumference as to position and extent;* i.e., *in all respects.*

180. COR. 3.—*Two circumferences can intersect in only two points.*

For, if they have three points common, they coincide, and form one and the same circumference.

PROPOSITION II.

181. Theorem.—*Two circumferences which intersect in one point, intersect also in a second point.*

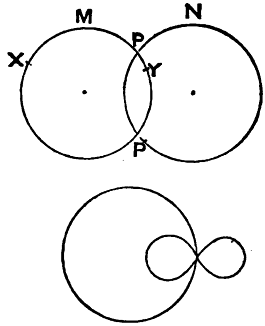

FIG. 143.

DEM.—Let M intersect N at P. As M passes from without to within the circle N, it has points both without and within. Now, for M to return into itself from any point within N, as Y, to any point without, as X, it must intersect N; but it cannot intersect in P, for a circumference does not intersect itself. Hence, it intersects in a second point, as P'. Q. E. D.

PROPOSITION III.

182. Theorem.—*If a straight line be drawn through the centres of two circles, of the intersections of either circumference with that line, the one on the side toward the centre of the other circle is the nearest point in this circumference to that centre, and the one on the opposite side is the farthest point from that centre.*

DEM.—Let M and N, or M' and N', be two circumferences whose centres are O and O'. Draw an indefinite line through these centres. Let A and H be the intersections of M or M' with this line, of which A is on the side of M or M' toward the centre O', and H is on the opposite side. Then is A the nearest point in M or M' to O', and H the farthest point from O'.

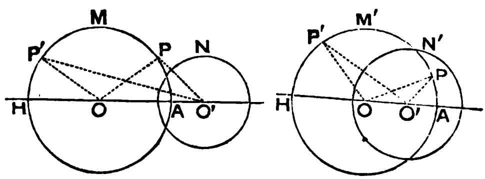

FIG. 144.

First, To show that A is nearer O' than any other point in the circumference. A will lie between O and O', in O', or beyond O'. When A lies between O and O', as in M, let P be any other point in M, and draw OP and O'P. Now OO' being a straight line, is less than OPO', a broken line. Subtracting OA from the former, and its equal OP from the latter, we have AO' < PO'. When A falls at O' the truth is self-evident. When A lies beyond O', as in M', let P be any other point in M', and draw OP and O'P. Now O'P + OO' > OP (= OA). Subtracting OO' from both, we have O'P > OA − OO' (= O'A). Hence, in any case, A is the nearest point in M or M' to O'.

Second, To show that H is the farthest point in M or M' from O'. In either

figure, let P' be any other point in the circumference than H, and draw OP' and $O'P'$. Now, $P'O + OO' > P'O'$. But $P'O = HO$. Hence $HO + OO'$ ($= HO'$) $> P'O'$

PROPOSITION IV.

183. Theorem.—*When the distance between the centres of two circles is greater than the sum of their radii, the circumferences are wholly exterior the one to the other.*

DEM.—Let M and N be the circumferences of two circles whose centres are O and O'. Let OO' be greater than the sum of the radii. Then are M and N wholly exterior the one to the other.

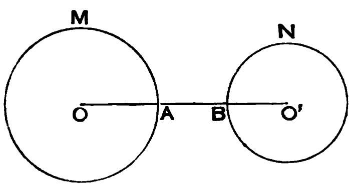

FIG. 145.

For A, the intersection of M with OO', is between O and O', since $OA < OO'$. Now, by hypothesis, $OO' > OA + BO'$. Subtracting OA from both, we have $AO' > BO'$. Hence, as the nearest point in M is farther from O' than the circumference of the latter circle, M lies wholly exterior to N. Q. E. D.

184. COR.—Conversely, *When two circumferences are exterior the one to the other, the distance between their centres is greater than the sum of their radii.*

DEM.—For, join the centres OO' with a straight line. Now the point A where this line cuts the circumference M is the nearest point in this circumference to the centre O'. But, by hypothesis, this (and every other point in circumference O) is without circle O'. Hence, $AO' > BO'$. To each add OA, and $OA + AO'$ (or OO') $> OA + BO'$.

PROPOSITION V.

185. Theorem.—*When the distance between the centres of two circles is equal to the sum of their radii, the circumferences are tangent to each other externally.*

DEM.—Let M and N be two circumferences, and OO', the distance between their centres, be equal to $OC + O'C'$, the sum of their radii; then are the circumferences tangent to each other externally.

The point A, where M cuts the line joining the centres, is between O and O′, since OA < OO′ by hypothesis. Moreover, A is the nearest point in M to the centre O′. Again, as OO′ = OC + O′C′, subtracting OA from the first member, and its equal OC from the other, we have O′A = O′C′; that is, A is in the circumference N. Hence, as A lies in N, and all other points in M are more distant from O′ than the length of the radius O′C′, M is entirely without N, except the point A, and the circles are tangent to each other externally. Q. E. D.

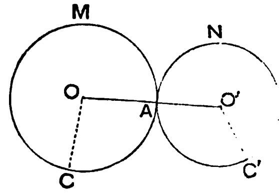

FIG. 146.

186. COR. 1.—Conversely, *When two circumferences are tangent to each other externally, the distance between their centres is equal to the sum of their radii.*

DEM.—M being tangent to N externally, the point in M nearest the centre O′ must be in N, while all other points in M are exterior to N. Now, the point in M nearest to O′ is A on the line joining their centres (***182***). A is therefore the point of tangency, and OO′ = OA + O′A.

187. COR. 2.—*When two circumferences are tangent to each other externally, the point of tangency is in the line joining their centres.*

PROPOSITION VI.

188. Theorem.—*When the distance between the centres of two circles is less than the sum and greater than the difference of their radii, the two circumferences intersect.*

DEM.—Let M and N be the circumferences of two circles whose centres are O and O′. Let the radius of M be equal to or greater than the radius of N. Now, if OO′ <OA + O′B, and > OA−O′B, M and N intersect.

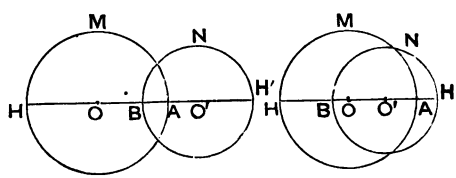

FIG. 147.

For, when OO′ > OA, OO′ < OA + O′B gives OO′ − OA (= AO′) < O′B; and when OO′ < OA, OO′ > OA − O′B gives O′B > OA − OO′ (= A′O). Hence the nearest point in M to O′ lies within N. Again, to the first member of OO′ > OA − O′B add HO, and to the second its equal OA, and we have OO′ + HO (= HO′) > 2OA − O′B. Now, since O′B $\overline{<}$ OA,* by hypothesis, the difference 2OA − O′B $\overline{>}$ O′B. Hence, HO′ > O′B, and H lies without N. As,

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* Read "O′B is equal to or less than OA."

therefore, M has one point at least within N and one without, M and N intersect. Q. E. D.

189. COR.—Conversely, *When two circumferences intersect, the distance between their centres is less than the sum and greater than the difference of their radii.*

DEM.—Let the radius of N be equal to or less than the radius of M. As the circumferences intersect the farthest point H′ of N from O must be farther from O than the length of the radius of M, *i. e.*, must lie without that circle. So we have by hypothesis $H'O > OA$. Subtracting $H'O'$ from the first member and its equal BO' from the second, we have $H'O - O'H' (= OO') > OA - BO'$; that is, the distance between the centres is greater than the difference of the radii. Again, as the nearest point in M to O′ must lie within N, we have $AO' < BO'$, and adding OA to both members, $OA + AO' (= OO') < OA + BO'$; that is, the distance between the centres is less than the sum of the radii.

PROPOSITION VII.

190. Theorem.—*When the distance between the centres of two unequal circles is equal to the difference of their radii, the less circumference is tangent to the other internally.*

DEM.—Let M and N be the circumferences of two circles whose centres O and O′ are so situated that $OO' = OC - O'C'$; then are the circles tangent to each other internally.

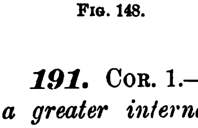

FIG. 148.

For, let N be the circumference of the less circle, so that $OC > O'C'$. Let HH′ be a diameter of M. By hypothesis $OO' = OC - O'C'$. Now, subtracting each member of this equality from OH′, we have $OH' - OO' (= O'H') = O'C'$. Whence it appears that H′, the point in N at the greatest distance from O, is in M; and, consequently, that every other point in N is within M. Hence, N is tangent to M internally. Q. E. D.

191. COR. 1.—Conversely, *When a less circumference is tangent to a greater internally, the distance between their centres equals the difference of their radii.*

DEM.—The less circumference N being tangent to the greater M, internally, the point in N at the greatest distance from the centre O of M, must be in M, while all other points of N lie within M. Now H′ in the line passing through the centres is the point of N at the greatest distance from O. Hence we observe that $OO' = OH' - O'H'$, *i. e.*, the difference between the radii.

192. COR. 2.—*When one circumference is tangent to another internally, the point of tangency is in the line passing through their centres.*

193. SCH.—If the radii are equal the two circumferences coincide.

PROPOSITION VIII.

194. Theorem.—*When the distance between the centres of two unequal circles is less than the difference of their radii, the less circumference is wholly within the greater.*

DEM.—Let N be a less circumference than M, and OO′, the distance between their centres, be less than OA − O′H′, the difference of their radii; then is N wholly within M.

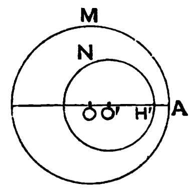

FIG. 149.

For, to each member of $OO' < OA - O'H'$ add O′H′, and we have $OO' + O'H' < OA$. But $OO' + O'H' = OH'$. Hence $OH' < OA$, and H′, the farthest point in N from O, is within M, and consequently N lies wholly within M. Q. E. D.

195. COR.—Conversely, *When a less circumference is wholly within a greater, the distance between their centres is less than the difference of their radii.*

DEM.—If N lies wholly within M, the farthest point in N from O, the centre of M, must be nearer O than is any point in M, *i. e.*, $OH' < OA$. Now, subtract O′H′ from each member, and we have $OH' - O'H'$ $(= OO') < OA - O'H'$. Q. E. D.

196. SCH.—If the centres coincide so that $OO' = 0$, the circumferences are said to be *concentric*. If, at the same time, their radii are equal, they are *coincident*.

PROPOSITION IX.

197. Theorem.—*When two circumferences intersect, the line which passes through their centres is perpendicular to their common chord at its middle point.*

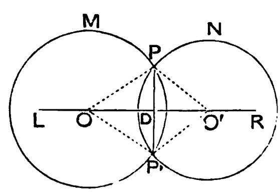

FIG. 150.

DEM.—Let the circumferences M and N intersect in the points P and P′ (*181*); let PP′ be the common chord, and LR the line passing through the centres O and O′; then is LR perpendicular to PP′.

For O′ is equally distant from the extremities P and P′, and O is also equally distant from P and P′. Hence, as LR has two points equally distant from the extremities of PP′, it is perpendicular to PP′ at its middle point. Q. E. D.

PROPOSITION X.

198. Theorem.—*When one circumference is tangent to another, either externally or internally, they have a common rectilinear* tangent at their common point.*

DEM.—Since the radii of the two circles drawn to the common point form one and the same straight line (*187, 192*), a line perpendicular to one at its extremity is perpendicular to the other also. And a line which is perpendicular to a radius at its extremity is tangent to the circle (*172*). Q. E. D.

199. COR.—*All circumferences having their centres in the same line, and having but one common point, are tangent to each other, and have a common rectilinear tangent at the common point.*

EXERCISES.

1. ***Prob.***—*To pass a circumference through three given points not in the same straight line.*

SUG.—The process should be gone through with as learned from PART I., and then the reasons for the process given as furnished by this section.

2. To pass a circumference through two given points, whose center shall be in a given line.

3. ***Prob.***—*To circumscribe a circumference about a given triangle, and give the reasons for the process.*

4. The centres of two circles whose radii are 10 and 7, are at 4 from each other. What is the relative position of the circumferences? What if the distance between the centres is 17? What if 20? What if 2? What if 0? What if 3?

---

* Straight line.

5. Given two circles O and O′, to draw two others, one of which shall be tangent to these externally, and to the other of which the two given circles shall be tangent internally. Give *all* the principles involved in the construction. Give other methods.

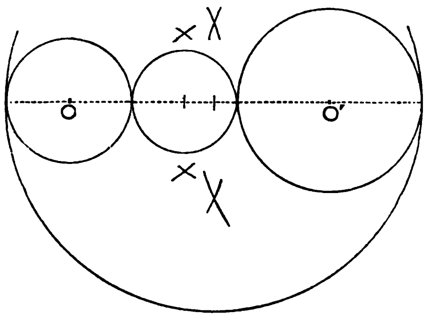

FIG. 151.

6. Given two circles whose radii are 6 and 10, and the distance between their centres 20. To draw a third circle whose radius shall be 8, and which shall be tangent to the two given circles? Can a third circle whose radius is 2 be drawn tangent to the two given circles? How will it be situated? Can one be drawn tangent to the given circles, whose radius shall be 1? Why?

SYNOPSIS.

RELATIVE POSITIONS OF CIRCUMFERENCES.

- PROP. I. Through three points.
  - *Cor.* 1. A circf. can be passed.
  - *Cor.* 2. A circf. determined by.
  - *Cor.* 3. Intersections of two circf's.
- PROP. II. Two circumferences which intersect in *one* point.
- PROP. III. Points in one circumference nearest to and farthest from the centre of another.
- DISTANCE BETWEEN CENTRES OF TWO CIRCLES.
  - PROP. IV. Greater than sum of radii.
    - *Cor.* Converse.
  - PROP. V. Equal to sum of radii.
    - *Cor.* 1. Converse.
    - *Cor.* 2. Point of tangency.
  - PROP. VI. Less than sum and greater than difference of radii.
    - *Cor.* Converse.
  - PROP. VII. Equal to diff. of radii.
    - *Cor.* 1. Converse.
    - *Cor.* 2. Point of tangency.
    - *Sch.* Radii equal.
  - PROP. VIII. Less than diff. of radii.
    - *Cor.* Converse.
    - *Sch.* Concentric, Coincident.
- PROP. IX. Perpendicular to common chord.
- PROP. X. Common tangent to two circles tangent to each other.
  - *Cor.* To all.
- EXERCISES.
  - *Prob.* To pass circumference through three points.
  - *Prob.* To circumscribe a triangle with a circumference.

SECTION VI.

OF THE MEASUREMENT OF ANGLES.

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200. Angles are said to be measured by arcs, according to the principles developed in the three following propositions.

PROPOSITION I.

201. Theorem.—*In the same or in equal circles, equal arcs subtend equal angles at the centre.*

Dem.—In the equal circles M and N, let *arc* AB = *arc* DC; then will the angles O and O′, called angles at the centre, be equal. For, placing N upon M so that O′ shall fall on O, and O′D on OA, since the circles are equal, D will fall on A; and since, by hypothesis, *arc* DC = *arc* AB, C will fall on B. Hence, O′C will coincide with OB, and *angle* O′ = *angle* O, because they coincide when applied. Q. E. D.

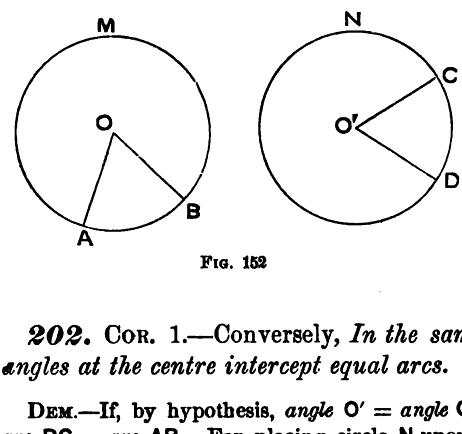

Fig. 152

202. Cor. 1.—Conversely, *In the same or in equal circles, equal angles at the centre intercept equal arcs.*

Dem.—If, by hypothesis, *angle* O′ = *angle* O, in the equal circles M and N, *arc* DC = *arc* AB. For, placing circle N upon M, so that O′ shall fall on O, and O′D on its equal OA, D falls on A, and, since *angle* O′ = *angle* O, O′C takes the direction OB, and, being equal to it, C falls on B. Hence, DC and AB coincide and are equal.

203. Cor. 2.—*A right angle at the centre intercepts a quarter of a circumference, and is said to be measured by it. Hence, a semicircumference is the measure of two right angles, and a whole circumference of four.*

PROPOSITION II.

204. Theorem.—*In the same or in equal circles, arcs which are in the ratio of two whole numbers subtend angles at the centre which have the same ratio, whence the angles are to each other as the arcs which subtend them.*

DEM.—In the equal circles M and N, let the arcs EF and IH, which subtend the angles O and O′ at the centre, be in the ratio of 5 to 8; then are the angles O and O′ in the ratio of 5 to 8, and we have

angle O : *angle* O′ :: *arc* EF : *arc* IH.

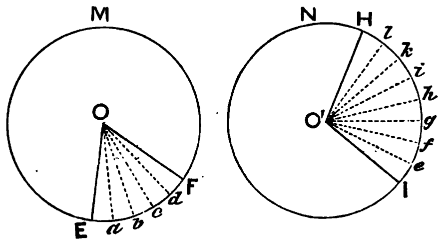

FIG. 153.

For, divide EF into 5 equal parts, as Ea, ab, etc., then IH can be divided into 8 such parts, Ie, ef, etc. Draw the radii Oa, Ob, Oc, etc., and O′e, O′f, O′g, etc.; and, since these partial arcs are equal, the partial angles which they subtend are equal, by the preceding proposition. Now, O is composed of 5 of these angles, and O′ of 8; whence

angle O : *angle* O′ :: 5 : 8.
But, *arc* EF : *arc* IH :: 5 : 8.

Hence, the two ratios being equal, we have

angle O′ : *angle* O : : *arc* IH : *arc* EF.

As the same method could be pursued in case the arcs were to each other as any other two whole numbers, the argument is general.

205. COR.—Conversely, *In the same or in equal circles, angles at the centre which are in the ratio of two whole numbers are to each other as their intercepted arcs.*

DEM.—Thus, let *angle* O′ be to *angle* O in the ratio of 8 to 5. Conceive O′ divided into 8 equal partial angles, then will O be divisible into 5 such partial angles. Now, the partial angles being equal, their intercepted arcs are equal, by the preceding proposition, *Cor.* 1. Whence,

arc IH : *arc* EF : : 8 : 5.
But, *angle* O′ : *angle* O : : 8 : 5, by hypothesis.
Hence, *arc* IH : *arc* EF : : *angle* O′ : *angle* O.

And the same method could be pursued with angles having the ratio of any other whole numbers.

PROPOSITION III.

206. Theorem.—*In the same circle or in equal circles, two incommensurable arcs are to each other as the angles which they subtend at the centre.*

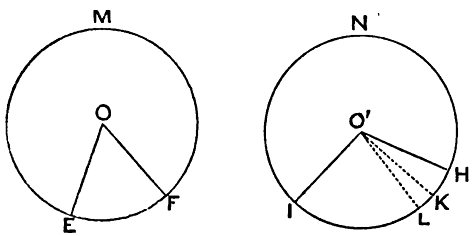

FIG. 154.

DEM.—In the equal circles M and N, let EF and IH be incommensurable arcs. Now there is some arc to which EF bears the same ratio as *angle* O to *angle* O′. If that arc is not IH let it be IL, an arc *less* than IH, so that

angle O : *angle* O′ : : *arc* EF : *arc* IL.*

Conceive EF divided into equal parts, each of which is less than LH,† the assumed difference between IH and IL. Then conceive one of these equal parts to be applied to IH as a measure, beginning at I. Since the measure is less than LH, at least one point of division must fall between L and H. Suppose K to be such a point. Draw O′K. Now, the arcs EF and IK are commensurable, and by the last proposition

angle O : *angle* IO′K : : *arc* EF : *arc* IK. But we assumed that

angle O : *angle* IO′H : : *arc* EF : *arc* IL.

In these proportions the antecedents being alike, the consequents should be proportional, so that

angle IO′K should be to *angle* IO′H : : *arc* IK : *arc* IL.

But this proportion is false, since

angle IO′K < *angle* IO′H, whereas *arc* IK > *arc* IL.

In a manner altogether similar (the student should supply it) we can show that

angle O is not to *angle* O′ : : *arc* EF : any *arc greater* than IH.

Hence, as the fourth term of the proportion cannot be less or greater than IH, it must be IH itself; and

angle O : *angle* O′ : : *arc* EF : *arc* IH. Q. E. D.

207. COR.—Conversely, *In the same or in equal circles, two incommensurable angles at the centre are to each other as the arcs which they intercept.*

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* This is a false hypothesis, and the object of the argument following is to show its falsity.

† This can be done by supposing EF bisected, then the halves bisected, then the fourths bisected, and this process of bisection continued until the parts are each less than LH.

DEM.—In the equal circles M and N, O and O′ being incommensurable angles at the centre, are to each other as the arcs EF and IH. If not, let us suppose

$$arc\ EF : arc\ IH :: angle\ O : angle\ IO'L, \text{ an angle less than } O'.$$

Divide O into equal partial angles, each less than LO′H, the assumed difference between IO′H and IO′L. Also conceive this angle to be applied as a measure to IO′H, beginning at O′I. At least one line of division will fall between O′L and O′H. Let O′K be such a line. Now, as O and IO′K are commensurable, we have by (*205*),

$$arc\ EF : arc\ IK :: angle\ O : angle\ IO'K.$$

But by supposition

$$arc\ EF : arc\ IH :: angle\ O : angle\ IO'L.$$

Therefore, since the antecedents are the same,

$$arc\ IK \text{ should be to } arc\ IH :: angle\ IO'K : angle\ IO'L.$$

But this is false, since

$$arc\ IK < arc\ IH, \text{ whereas } angle\ IO'K > angle\ IO'L.$$

Whence we learn that the fourth term of the proportion cannot be less than *angle* IO′H. In a similar manner it can be shown (let the student do it) that it cannot be greater. Hence it must be IO′H itself; and

$$arc\ EF : arc\ IH :: angle\ O : angle\ IO'H.$$

208. SCH.—Out of the truths developed in the three preceding propositions grows the method of representing angles by degrees, minutes, and seconds, as given in Trigonometry (PART IV., *3–6*). It will be observed, that in all cases, if arcs be struck *with the same radius*, from the vertices of angles as centres, the angles bear the same ratio to each other as the arcs intercepted by their sides. Hence the arc is said to measure the angle. Though this language is convenient, it is not quite natural; for we naturally measure a quantity by another of *like kind*. Thus, *distance* (length) we measure by *distance*, as when we say a line is 10 inches long. The line is *length;* and its measure, an inch, is *length* also. So, likewise, we say the area of a field is 4 acres: the quantity measured is *a surface;* and the measure, an acre, is *a surface* also. Yet, notwithstanding the artificiality of the method of measuring angles by arcs, instead of directly by angles, it is not only convenient but universally used; and the student must know just what is meant by it. For example, a circumference is conceived as divided into 360 equal arcs, called degrees. Hence, as a right angle at the centre is subtended by one-fourth of the circumference, it is called an angle of 90 degrees. 180 degrees is the measure of two right angles, 45 degrees, of half a right angle, etc. Thus we get a perfectly definite idea of the

magnitude of an angle from the statement of the number of degrees which measure it; and, for brevity, the angle is spoken of as an angle of the same number of degrees as the intercepted arc.

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209. ***An Inscribed Angle*** is an angle whose vertex is in a circumference, and whose sides are chords, or a chord and diameter, of that circumference.

PROPOSITION IV.

210. Theorem.—*An inscribed angle is measured by half the arc intercepted between its sides.*

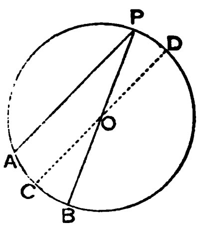

FIG 155

DEM.—*First, when one side is a diameter.* Let APB be an inscribed angle, and PB a diameter; then is APB measured by one-half of arc AB. For, through the centre O, draw the diameter DC parallel to the chord PA; then COB = POD (*134*), whence *arc* CB = *arc* PD (*202*), also COB = APB (*152*); and *arc* PD = *arc* AC (*174*), whence PD = CB = $\frac{1}{2}$AB. Now COB is measured by CB (*208*); hence APB is measured by CB = $\frac{1}{2}$AB. Q. E. D.

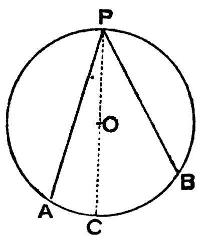

FIG. 156.

Second, when both sides are chords and the centre of the circle lies between them. Let APB be such an angle. Draw the diameter PC. Now, by the preceding part, APC is measured by $\frac{1}{2}$AC, and CPB by $\frac{1}{2}$CB. Hence APC + CPB, or APB, is measured by $\frac{1}{2}$AC + $\frac{1}{2}$CB, or $\frac{1}{2}$AB. Q. E. D.

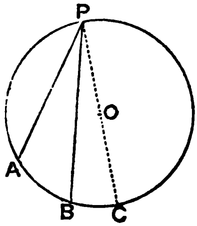

FIG. 157.

Third, when both sides are chords and the centre lies without the angle. Let APB be such an angle. Draw the diameter PC. Now APC is measured by $\frac{1}{2}$AC, and BPC by $\frac{1}{2}$BC. Hence APC − BPC, or APB, is measured by $\frac{1}{2}$AC − $\frac{1}{2}$BC, or $\frac{1}{2}$AB. Q. E. D.

***211.* Cor.**—*In the same or equal circles all angles inscribed in the same segment, intercept equal arcs, and are consequently equal. If the segment is less than a semicircle, the angles are obtuse; if a semicircle, right; if greater than a semicircle, acute.*

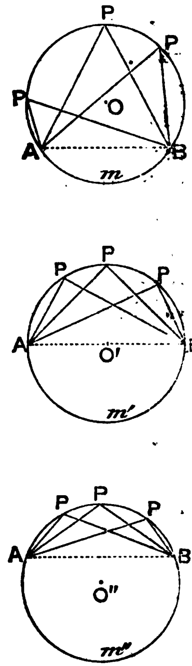

Fig. 158.

Ill.—In each separate figure the angles P are equal, for they are each measured by half the same arc. . . . In O, each angle P is acute, being measured by $\frac{1}{2}m$, which is less than a quarter of a circumference. . . . In O′, each angle P is a right angle, being measured by $\frac{1}{2}m'$, which is a quadrant (quarter of a circumference.) . . . In O″, each angle P is obtuse, being measured by $\frac{1}{2}m''$, which is greater than a quadrant.

PROPOSITION V.

***212.* Theorem.**—*Any angle formed by two chords intersecting in a circle is measured by one-half the sum of the arcs intercepted between its sides and the sides of its vertical, or opposite, angle.*

Dem.—Let the chords AB and CD intersect at P; then is APD, or its equal CPB, measured by $\frac{1}{2}$(AD + CB); and APC, or its equal BPD, is measured by $\frac{1}{2}$(AC + BD).

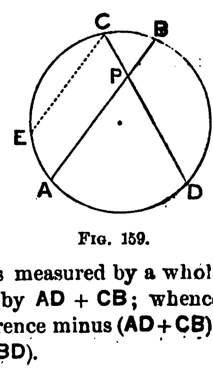

Fig. 159.

For, through C draw CE parallel to BA; whence ECD = APD (*152*), and CB = EA (*174*). But ECD is measured by $\frac{1}{2}$ ED (*210*), which equals $\frac{1}{2}$ (AD + EA) = $\frac{1}{2}$(AD + CB).

That APC, or its equal BPD, is measured by $\frac{1}{2}$(AC + BD), appears from the fact that the sum of the four angles about P being equal to four right angles, is measured by a whole circumference (*208*). But APD + CPB is measured by AD + CB; whence APC + BPD, or 2 APC, is measured by the whole circumference minus (AD + CB); that is, by AC + BD. Then is APC measured by $\frac{1}{2}$(AC + BD).

213. SCH.—The case of the angle included between two chords passes into that of the inscribed angle in the preceding proposition, by conceiving **AB** to move parallel to its present position until **P** arrives at **C** and **BA** coincides with **CE**. The angle **APD** is all the time measured by half the sum of the intercepted arcs; but, when **P** has reached **C**, **CB** becomes 0, and **APD** becomes an inscribed angle measured by half its intercepted arc.

In a similar manner we may pass to the case of an angle at the centre, by supposing **P** to move toward the centre. All the time **APD** is measured by $\frac{1}{2}$(**AD** + **CB**); but, when **P** reaches the centre, **AD** = **CB**, and $\frac{1}{2}$(**AD** + **CB**) = $\frac{1}{2}$(**2AD**) = **AD**; *i. e.*, an angle at the centre is measured by its intercepted arc.

PROPOSITION VI.

214. Theorem.—*An angle formed by two secants meeting without the circle is measured by one-half the difference of the intercepted arcs.*

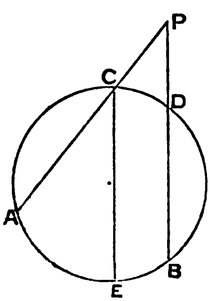

FIG. 100.

DEM.—Let **APB** be an angle formed by the two secants **AP** and **PB**; then is it measured by $\frac{1}{2}$(**AB** – **CD**), *i. e.*, one-half the intercepted arcs.

For, draw **CE** parallel to **PB**; then **CD** = **EB** (*174*), and **ACE** = its opposite interior angle **APB**. But **ACE** is measured by $\frac{1}{2}$**AE** = $\frac{1}{2}$(**AB** – **EB**) = $\frac{1}{2}$(**AB** – **CD**). Q. E. D.

215. SCH.—This case passes into that of an inscribed angle, by conceiving **P** to move toward **C**, thus diminishing the arc **CD**. When **P** reaches **C**, the angle becomes inscribed; and, as **CD** is then 0, $\frac{1}{2}$(**AB** – **CD**) = $\frac{1}{2}$**AB**. Also, by conceiving **P** to continue to move along **PA**, **CD** will reappear *on the other side of* **PA**, hence will change its sign,* and $\frac{1}{2}$(**AE** – **CD**) will become $\frac{1}{2}$(**AE** + **CD**), as it should, since the angle is then formed by two chords intersecting within the circumference.

PROPOSITION VII.

216. Theorem.—*An angle formed by a tangent and a chord drawn from the point of tangency is measured by one-half the intercepted arc.*

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* In accordance with the law of positive and negative quantities as used in mathematics, whenever a continuously varying quantity is conceived as diminishing till it reaches 0, and then as reappearing by the same law of change, it must change its sign.

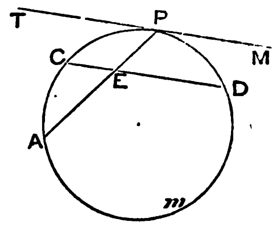

FIG. 161.

DEM.—Let TPA be an angle formed by TM tangent at P, and the chord PA; then is TPA measured by one-half the intercepted arc AP. For, draw any chord CD parallel to TM and cutting AP. Then CEA = TPA. But CEA is measured by $\frac{1}{2}$ (AC + PD). Hence, as PD = CP (*175*), TPA is measured by $\frac{1}{2}$ (AC + CP), or $\frac{1}{2}$ AP. Q. E. D.

Show that APM is measured by $\frac{1}{2}$ arc A*m*P.

Also, observe how the case of two secants (*214*) passes into this.

PROPOSITION VIII.

217. Theorem.—*An angle formed by two tangents is measured by one-half the difference of the intercepted arcs.*

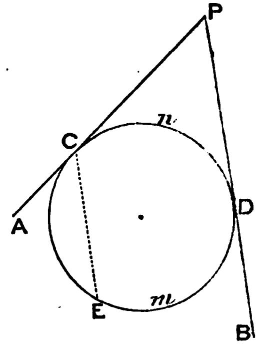

FIG. 162.

DEM.—Let APB be an angle formed by the two tangents AP and PB; then is it measured by $\frac{1}{2}$ (*arc* C*m*D – *arc* C*n*D), *i. e.*, one-half the difference of the intercepted arcs. For, through one of the points of tangency, as C, draw a chord, as CE, parallel to the other tangent. Now, ACE is measured by $\frac{1}{2}$ *arc* CE, by the last proposition. But ACE = APB, and *arc* CE = C*m*D – D*m*E = C*m*D – C*n*D, since C*n*D = E*m*D (*175*). Hence, APB is measured by $\frac{1}{2}$ (C*m*D – C*n*D). Q. E. D.

218. SCH.—The case of two secants (*214*) passes into this by supposing the secants to separate until they become tangents.

EXERCISES.

1. ***Prob.***—*Through a given point to draw a parallel to a given line, on the principles contained in* (*152*), (*201*), *and* (*165*).

SOLUTION.—Through P to draw a parallel to AB. From P as a centre, with any radius greater than the distance from P to AB, describe an arc cutting AB, as *ac*. From *a* as a centre, with the same radius, strike an arc through P, intersecting AB, as P*b*. Take the chord P*b* and apply it from *a* on the arc *ac*, as *a*O. These chords being equal, the arcs P*b* and

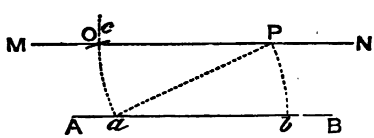

FIG. 163.

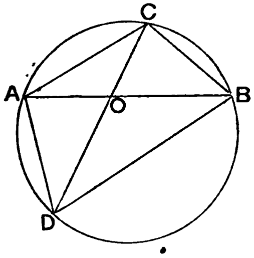

FIG. 164.

aO are equal (*165*). Again, angle Pab = angle OPa, since they are measured by equal arcs struck with the same radius (*201*). These alternate angles being equal, MN is parallel to AB (*152*).

2. In *Fig.* 164 there are 4 pairs of equal angles. Which are they, and why? Show also that COB = ABD + CDB, by (*210*), and (*212*). Show also that DOB = ABC + DAB.

3. ***Prob.***—*From a point without a circle to draw a tangent to the circle.*

SOLUTION.—Let O be the given circle, and P the given point. Join P with the centre O, and upon PO as a diameter describe a circle. Let T and T′ be the intersections of the two circumferences. Now, if lines be drawn from P through T and T′, they will be tangent to the circle O. For OTP and OT′P, being inscribed in semi-circles, are right angles (*211*). Hence, PM is perpendicular to radius OT at its extremity T, and is therefore a tangent (*172*). In like manner PT′ is shown to be a tangent, and we see that *from a point without a circle two tangents can be drawn to the circle.*

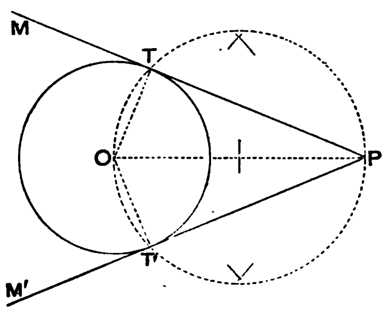

FIG. 165.

4. ***Prob.***—*On a given line, to construct a segment which shall contain a given angle.*

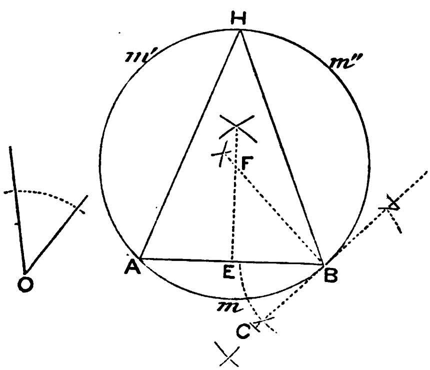

FIG. 166.

SOLUTION.—Let AB be the given line, and O the given angle. At one extremity of the given line, as B, construct an angle ABC equal to the given angle O, which shall lie on the opposite of AB from that on which the required segment is to lie. Erect a perpendicular to the line CB at B, and also a perpendicular bisecting AB. Let FB and FE be

these perpendiculars, intersecting at F. From F as a centre, with a radius equal to FB, describe a circle. Then is AHB the segment required. For, CB being perpendicular to radius FB at its extremity, is tangent to the circle, and *angle* ABC (= *angle* O) is measured by ½ of arc A*m*B (***216***). Now, any angle inscribed in the segment A*m′m″*B, as AHB, has ½ A*m*B for its measure, and is, consequently, equal to O.

Another Solution.—On the side of AB on which the segment is to lie, draw *any* line through either extremity of AB, *making an acute angle* with AB. Let CB be such a line. At *any* point in CB, as C, draw a line CE, making angle ECB = the given angle O, *Fig.* 166. Through A pass a parallel to CE (see *Ex.* 1), as AD. Pass a circumference through A, D, and B. Any angle inscribed in segment A*m*B is equal to O. [Let the student give all the reasons, and make the construction. The requisite marks for the construction are made in the figure. Why is it said, make CBA an *acute angle?* When would a right angle answer? When an obtuse angle?]

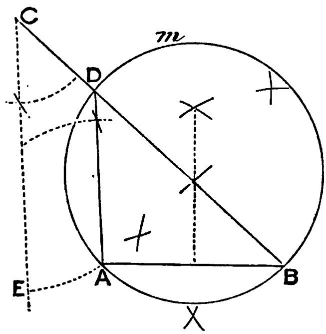

Fig. 167.

SYNOPSIS.

Measurement of Angles.

- How angles are measured.
- Fundamental Propositions.
  - Prop. I. Equal arcs subtend equal angles at the centre.
    - *Cor.* 1. Converse.
    - *Cor.* 2. Measure of 1, 2, and 4 right angles.
  - Prop. II. Commensurable arcs in the same ratio as their subtended angles.
    - *Cor.* Converse.
  - Prop. III. Incommensurable arcs.
    - *Cor.* Converse.
    - *Sch.* Method of measuring angles.
- Inscribed angle, what?
- Prop. IV. Inscribed angle, how measured.
  - *Cor.* In segment, >, =, or < semicircle.
- Prop. V. Angle between two chords.
  - *Sch.* Compared with preceding.
- Prop. VI. Angle between two secants.
  - *Sch.* Compared with Prop. IV.
- Prop. VII. Angle between tangent and chord.
- Prop. VIII. Angle between two tangents.
  - *Sch.* Compared with Prop. VI.
- Exercises.
  - *Prob.* To draw a parallel through a given point.
  - *Prob.* To draw a tangent to a circle from a point without.
  - *Prob.* To construct a segment on a given line which shall contain a given angle.

SECTION VII.

OF THE ANGLES OF POLYGONS, AND THE RELATION BETWEEN THE ANGLES AND SIDES.

OF TRIANGLES.

PROPOSITION I.

219. Theorem.—*The sum of the three angles of a triangle is two right angles.*

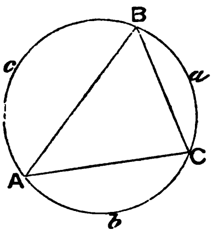

FIG. 168.

DEM.—Conceive a circumference passed through the vertices of the triangle, as *abc*, through the vertices of the triangle ABC (*58*). The angle A is measured by $\frac{1}{2}$ *arc a*, B by $\frac{1}{2}$ *b*, and C by $\frac{1}{2}$ *c*. Hence, A + B + C is measured by $\frac{1}{2}$ $(a + b + c)$, or a semi-circumference, and is equal to two right angles (*203*). Q. E. D.

220. COR. 1.—*A triangle can have only one right angle, or one obtuse angle.* Why?

221. COR. 2.—*Two angles of a triangle, or their sum, being given, the third may be found by subtracting this sum from two right angles,* i. e., *either angle is the supplement of the other two.*

222. COR. 3.—*The sum of the two acute angles of a right-angled triangle is equal to one right angle;* i.e., *they are complements of each other.*

223. COR. 4.—*If the angles of a triangle are equal each to each, any one is one-third of two right angles, or two-thirds of one right angle.*

PROPOSITION II.

224. Theorem.—*The sides of a triangle sustain the same* GENERAL *relation to each other as their opposite angles; that is, the greatest side is opposite the greatest angle, the second greatest side opposite the second greatest angle, and the least side opposite the least angle.*

DEM.—In the triangle ABC let C > B > A be the order of the values of the angles; then AB > AC > BC is the order of the values of the sides. For, circumscribe the circumference *abc*. The angle C being greater than B, the arc *c*, the half of which measures C, is greater than the arc *b*, the half of which measures B. Now, the greater arc has the greater chord (*166*). Hence, AB > AC. In like manner, if B > A, arc *b* > arc *a*, and AC > BC. If either angle, as C, is obtuse, AB is greater than AC or BC, because it lies nearer the centre (*167*).

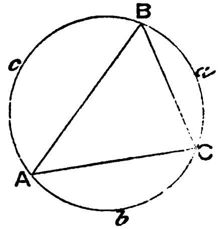

FIG. 169.

225. COR. 1.—Conversely, *The order of the magnitudes of the sides being* AB > AC > BC, *the order of the magnitudes of the angles is* C > B > A.

[Let the student give the demonstration in form.]

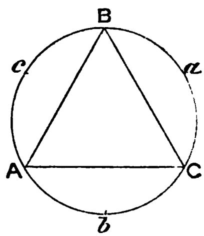

FIG. 170.

226. COR. 2.—*An equiangular triangle is also equilateral; and, conversely, an equilateral triangle is equiangular.*

DEM.—If A = B = C, arc *a* = arc *b* = arc *c*, and, consequently, chord BC = chord AC = chord AB. Conversely, if the chords are equal, the arcs are, and hence the angles subtended by these arcs.

227. COR. 3.—*In an isosceles triangle the angles opposite the equal sides are equal; and, conversely, if two angles of a triangle are equal, the sides opposite are equal, and the triangle is isosceles.*

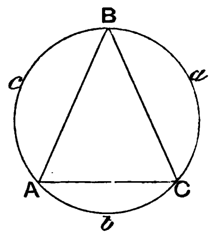

FIG. 171.

DEM.—If AB = BC, arc *a* = arc *c*; and hence, angle A, measured by $\frac{1}{2}$ *a*, = angle C, measured by $\frac{1}{2}$ *c*. Conversely, if A = C, arc *a* = arc *c*; and hence chord BC = chord AB.

228. SCH.—It should be observed that the proposition gives only the *general* relation between the angles and sides of a triangle. It is not meant that the sides are *in the same ratio* as their opposite angles: this is not true. Thus in *Fig.* 172 angle *c* is twice as great as angle *a*; but side *c* is not *twice* as great as side *a*, although it *is greater*. Trigonometry discovers the *exact* relation which exists between the sides and angles.

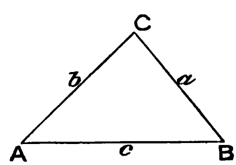

FIG. 172.

PROPOSITION III.

229. ***Theorem.***—*If from any point within a triangle lines be drawn to the extremities of any side, the included angle is greater than the angle of the triangle opposite this side.*

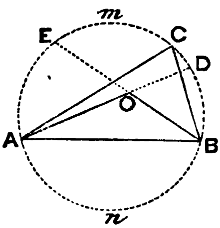

FIG. 173.

DEM.—Let OA and OB be two lines drawn from any point O within the triangle ABC, to the extremities of the side AB; then angle AOB > ACB.

For, circumscribe a circle about the triangle. Now, ACB is measured by $\frac{1}{2}$ A*n*B, but AOB is measured by $\frac{1}{2}$ (A*n*B + E*m*D). Therefore, AOB > ACB. Q. E. D.

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230. ***An Exterior Angle*** of a polygon is an angle formed by any side with its adjacent side produced, as CBD, *Fig.* 174.

PROPOSITION IV.

231. ***Theorem.***—*An exterior angle of a triangle is equal to the sum of the two interior non-adjacent angles.*

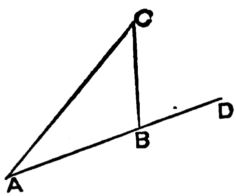

FIG. 174.

DEM.—Let ABC be any triangle, and CBD an exterior angle; then CBD = A + C.

For CBD is the supplement of CBA by (*131*), and CBA is the supplement of A + C by (*221*). Hence, CBD = A + C. Q. E. D.

232. COR.—*Either angle of a triangle not adjacent to a specified exterior angle, is equal to the difference of this exterior angle and the other non-adjacent angle.*

Thus, since CBD = A + C, by transposition, CBD − A = C, and CBD − C = A.

OF QUADRILATERALS.

PROPOSITION V.

233. Theorem.—*The sum of the angles of a quadrilateral is four right angles.*

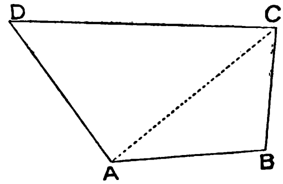

FIG. 175.

DEM.—Let ABCD be any quadrilateral; then DAB + ABC + BCD + CDA = four right angles.

For, draw either diagonal, as AC, dividing the quadrilateral into two triangles. Then, as the sum of the angles of the two triangles is the same as the sum of the angles of the quadrilateral, and the sum of the angles of the triangles is twice two right angles (*219*); the sum of the angles of the quadrilateral is four right angles. Q. E. D.

PROPOSITION VI.

234. Theorem.—*The opposite angles of any quadrilateral which can be inscribed in a circle are supplementary.*

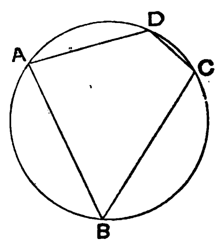

FIG. 176.

DEM.—Let ABCD be any inscribed quadrilateral; then A + C = two *right angles*, and D + B = two *right angles*.

For, A is measured by ½ *arc* BCD, and C is measured by ½ *arc* DAB (*210*). Hence, A + C is measured by one-half a circumference, and is, therefore, equal to two right angles (*203*). In like manner D is measured by ½ *arc* ABC, and B by ½ *arc* ADC. Consequently, D + B is measured by one-half a circumference, and is, therefore, equal to two right angles.

PROPOSITION VII.

235. Theorem.—*The opposite angles of a parallelogram are equal, and the adjacent angles are supplementary.*

DEM.—ABCD, *Fig.* 177, being any parallelogram, A = C, B = D, and B + C, C + D, D + A, and A + B, each = *two right* angles.

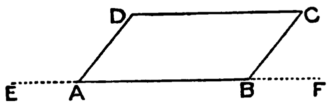

FIG. 177.

For, produce any side, as AB, forming the two exterior angles EAD and CBF. Since CB and DA are parallel, and FE cuts them, the opposite exterior and interior angles, CBF and DAB are equal (*149*). Again, since EF and DC are parallel, and CB cuts them, the alternate interior* angles CBF and C are equal (*149*). Hence, as DAB and C are each equal to CBF, they are equal to each other. In a similar manner D can be proved equal to CBA. [Let the student give the proof.]

That the angles B and C of the parallelogram are supplemental is evident from (*150*), which proves that the sum of two interior angles on the same side of a secant cutting two parallels is two right angles. For a like reason A + D = *two right angles*, etc.

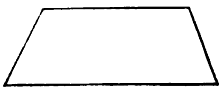

FIG. 178.

236. COR. 1.—*The two angles of a trapezoid adjacent to either one of the two sides not parallel are supplemental.*

[Let the student show why.]

237. COR. 2.—*If one angle of a parallelogram is right, the others are also, and the figure is a rectangle.*

PROPOSITION VIII.

238. Theorem.—Conversely to the last, *If the adjacent angles of a quadrilateral are supplementary, or the opposite angles equal, the figure is a parallelogram.*

DEM.—If A + D = two right angles, AB and DC are parallel by (*147*). For a like reason, if D + C = two right angles, DA and CB are parallel. Again, if A = C and D = B, by adding we have A + D = C + B. But A + D + C + B = four right angles (*233*). Hence, A + D = two right angles, and AB and CD are parallel. So, also, A + B can be shown to be equal to two right angles; and, consequently, AD and CB are parallel.

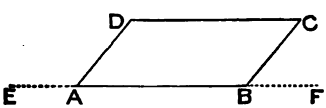

FIG. 179.

* Interior with reference to the parallels (146).

PROPOSITION IX.

239. Theorem.—*If two opposite sides of a quadrilateral are equal and parallel, the figure is a parallelogram.*

Dem.—In (*a*) let DC be equal and parallel to AB; then is ABCD a parallelogram.

For, drawing the diagonal AC, it makes the angles ACD and CAB equal, since they are alternate interior angles (*149*). Conceive the quadrilateral divided in this diagonal into two triangles, as in (*b*). Reverse the triangle ACB and place it as in (*c*). Draw DB. Since angle DCA = angle CAB, and DC = BA, if CBA be revolved upon AC, AB will take the direction CD, B will fall in D, and CBA will coincide with ADC. Hence, angle ACB = angle DAC. But in (*a*) these are alternate interior angles made by AC with AD and BC. Therefore, AD is parallel to BC (*152*). Q. E. D.

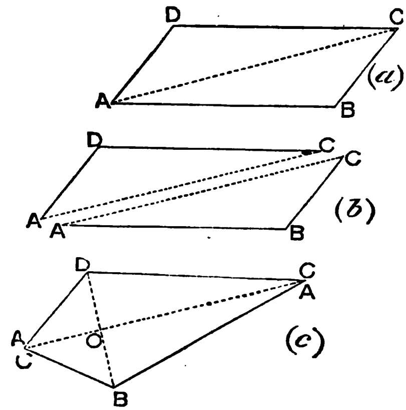

Fig. 180

PROPOSITION X.

240. Theorem.—*If the opposite sides of a quadrilateral are equal, the figure is a parallelogram.*

Dem.—In (*a*) let AB = DC, and AD = BC; then is ABCD a parallelogram.

For, divide the quadrilateral in the diagonal AC, and reversing the triangle ABC, place it as in (*c*), and draw DB. Since AB = CD, and CB = AD, DB is perpendicular to CA (*130*). Now, revolving ABC upon CA, it will coincide with ADC. Hence, angle DCA = angle CAB, and AB is parallel to DC. Also, angle DAC = angle BCA, and AD is parallel to BC. Therefore, ABCD is a parallelogram. Q. E. D.

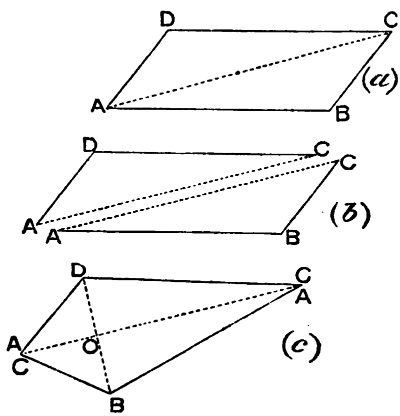

Fig. 181.

PROPOSITION XI.

241. Theorem.—Conversely to the last, *The opposite sides of a parallelogram are equal.*

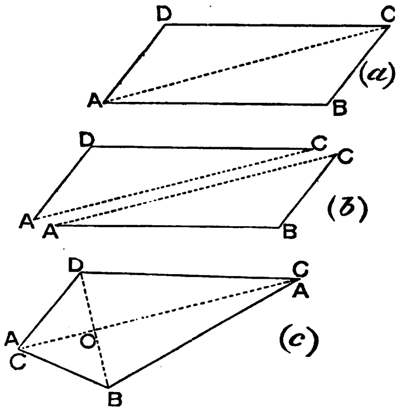

FIG. 182.

DEM.—Let ABCD be a parallelogram; then AB = DC, and AD = CB.

Since DC is parallel to AB, angle DCA = angle CAB. Also, since AD is parallel to BC, angle DAC = angle ACB (*152*). Now, divide the parallelogram (*a*) in the diagonal, and place ABC as in (*c*). Revolve ABC on AC, until it falls in the plane on the other side of AC. Since angle BAC = angle ACD, AB will take the direction CD, and B will fall in CD, or CD produced. Since angle BCA = angle DAC, CB will take the direction AD, and B will fall in AD, or in AD produced. Therefore, as B falls at the same time in AD and CD, it falls at the intersection D, and the triangles coincide. Hence, AB = CD, and AD = CB. Q. E. D.

242. COR. 1.—*Parallels intercepted between parallels are equal.*

243. COR. 2.—*A diagonal of a parallelogram divides it into two equal triangles.*

PROPOSITION XII.

244. Theorem.—*The diagonals of a parallelogram mutually bisect each other.*

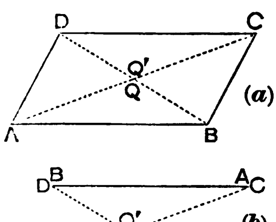

FIG. 183.

DEM.—Let AC and DB be the diagonals of the parallelogram ABCD (*a*), and Q their intersection; then, DQ = QB, and AQ = QC.

For, take the triangle AQB, and apply it to DQ′C, by placing BA in its equal DC, B falling at D, and A at C, with the vertices Q and Q′ on the same side of this common line, as in (*b*). Now, since angle QBA = Q′DC (*152*), BQ will take the direction DQ′, and Q will fall in DQ′, or in DQ′ produced. For a like reason AQ will take the direction CQ′, and Q will fall in CQ′, or in CQ′ produced. Hence, as Q falls at the same time in DQ′ and CQ′, it falls at their intersection Q′; whence BQ = DQ′, and AQ = CQ′. Q. E. D.

PROPOSITION XIII.

245. Theorem.—*The diagonals of a rhombus bisect each other at right angles.*

DEM.—Let AC and DB be the diagonals of the rhombus ABCD; then are they at right angles to each other, and bisected at Q.

For, since $AB = AD$, and $DC = CB$, AC has two of its points equally distant from D and B, and is, therefore, perpendicular to DB, at its middle point (*130*). In like manner D and B are each equidistant from A and C, whence Q is the middle point of AC.

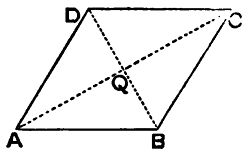

FIG. 184.

246. COR.—*The diagonals of a rhombus bisect its angles.*

For, revolve ABC upon AC as an axis, and it will coincide with ADC. Hence angles A and C are bisected. In like manner revolve DAB upon DB, and it will coincide with DCB. Hence D and B are bisected.

PROPOSITION XIV.

247. Theorem.—*The diagonals of a rectangle are equal.*

DEM.—Let AC and DB be the diagonals of the rectangle ABCD; then $AC = DB$.

For, upon AC as a diameter describe a circle. Since D and B are right angles, they are inscribed in semicircles (*211*), and DB is a diameter. Therefore, $AC = DB$. Q. E. D.

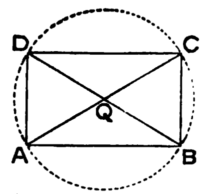

FIG. 185.

248. COR.—Conversely, *If the diagonals of a parallelogram are equal, the figure is a rectangle.*

DEM.—Since the diagonals of a parallelogram bisect each other, if they are equal, a circumference described from their intersection as a centre, with a radius equal to half of a diagonal, will pass through the vertices of the parallelogram. Hence the diagonals will be diameters, and the angles will be inscribed in semicircles, and consequently will be right angles.

OF POLYGONS OF MORE THAN FOUR SIDES.

249. A Salient Angle of a polygon is one whose sides, when produced, can only extend *without* the polygon.

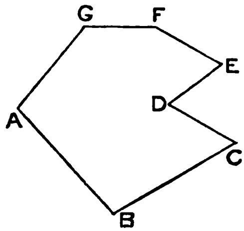

FIG. 186.

250. A Re-entrant Angle of a polygon is one whose sides, when produced, can extend *within* the polygon.

ILL.—In the polygon ABCDEFG, all the angles are salient except D, which is re-entrant.

251. A Convex Polygon is a polygon which has only salient angles. A polygon is always supposed to be convex, unless the contrary is stated.

252. A Concave or Re-entrant Polygon is a polygon with at least one re-entrant angle.

PROPOSITION XV.

253. Theorem.—*The sum of the interior angles of a polygon is equal to twice as many right angles as the polygon has sides, less four right angles.*

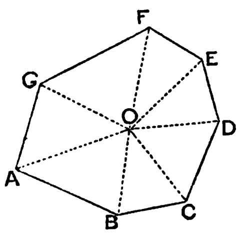

FIG. 187.

DEM.—Let n be the number of sides of any polygon; then the sum of its angles is

n times *two right angles* — 4 *right angles.*

For, from any point O, within, draw lines to the vertices of the angles. As many triangles will thus be formed as the polygon has sides, that is, n. The sum of the angles of these triangles is

n times *two right angles* (***219***).

But this exceeds the sum of the angles of the polygon by the sum of the angles at the common vertex O, that is, by 4 *right angles.* Hence the sum of the angles of the polygon is

n times *two right angles* — 4 *right angles.* Q. E. D.

254. SCH. 1.—The sum of the angles of a pentagon is 5 times *two right angles* — 4 *right angles*, or 6 *right angles.* The sum of the angles of a hexagon is 8 *right angles;* of a heptagon, 10; of an octagon, 12, etc.

255. SCH. 2.—This proposition is equally applicable to triangles and to quadrilaterals. Thus the sum of the angles of a triangle is 3 times *two right angles* — 4 *right angles* (or 6 — 4) = 2 right angles. So also the sum of the angles of a quadrilateral is 4 times *two right angles* — 4 *right angles*, or 4 right angles.

256. SCH. 3.—To find the value of an angle of an equiangular polygon, that is, one whose angles are equal each to each, divide the sum of all the angles by the number of angles.

PROPOSITION XVI.

257. ***Theorem.***—*If the sides of a polygon be produced so as to form one exterior angle (and only one) at each vertex, the sum of these exterior angles is four right angles.*

DEM.—Let n be the number of sides of any polygon. At each of the n angles, there is an interior and an exterior angle, whose sum, as A + a, is two right angles. Hence the sum of all the exterior and interior angles is n times *two right angles.* Now, from this sum subtracting the sum of the exterior angles, the remainder is the sum of the interior angles. But, by the preceding proposition, 4 *right angles* subtracted from n times *two right angles*, leaves the sum of the interior angles. Therefore the sum of the exterior angles is 4 *right angles.* Q. E. D.

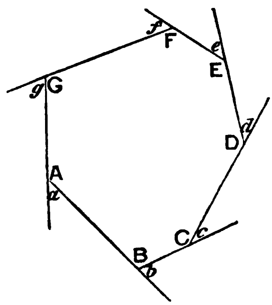

FIG. 188.

OF REGULAR POLYGONS.

PROPOSITION XVII.

258. ***Theorem.***—*The angles of an inscribed equilateral polygon are equal; and the polygon is regular.*

DEM.—Let ABCDEF be an inscribed polygon, with AB = BC = CD, etc.: then is angle A = B = C = D, etc., and the polygon is regular.

For, from the centre of the circle draw OF, OA, and OB, and also the perpendiculars Oa and Ob. Revolve OFA upon OA as an axis, until it falls in the

plane of OAB. Since the chords FA and AB are equal, the *arc* FA = *arc* AB, and F falls at B. Hence the triangles OFA and OAB coincide. The angle A of the polygon is therefore bisected by OA; that is, OAF = OAB. In the same manner OBA can be shown equal to OBC. Moreover, since OA and OB are equal oblique lines drawn from a point in the perpendicular, *angle* OAB = *angle* OBA. Hence, as the half of A equals the half of B, A = B. In like manner, B can be shown equal to C, C to D, D to E, etc. Therefore the polygon is equiangular, as well as equilateral, and consequently regular (***117***). Q. E. D.

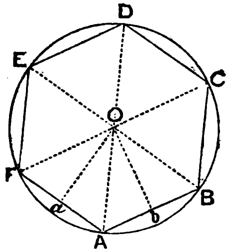

Fig. 189.

PROPOSITION XVIII.

259. Theorem.—*The sides of an inscribed equiangular polygon are equal when their number is* ODD; *and the polygon is regular.*

Dem.—Let ABCDEFG be an inscribed equiangular polygon of an *odd* number of sides; then is side AB = BC = CD, etc., and the polygon is regular.

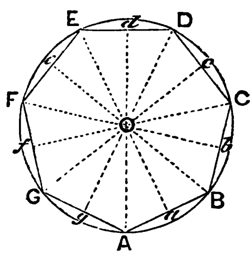

Fig. 190.

For, from the centre of the circle draw the radii OA, OB, etc., to the vertices of the polygon, and O*a*, O*b*, etc., perpendicular to the sides. Revolve the quadrilateral OGA*a*, upon O*a* as an axis until it falls in the plane of OCB*a*. Since O*a* is perpendicular to the chord AB, A*a* = *a*B, and A will fall at B. Also, as the angle A of the polygon = B, AG will fall in BC. Now G falls at the same time in the arc BCD (***158***) and in BC, and hence falls at their intersection C. Therefore AG = BC. In like manner revolving OBC*c* upon O*c* as an axis, BC is found equal to ED. So also we can show that ED = FG; then that FG = AB; then that AB = DC; and finally, that DC = EF. Hence we have GA = BC = ED = FG = AB = DC = EF; and as the polygon is equiangular by hypothesis, it is regular (***117***). Q. E. D.

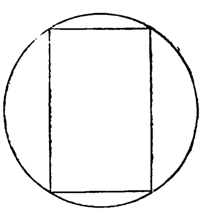
Fig. 191.

260. Sch.—It is easy to see that the above argument would fail in the case of a polygon of an even number of sides, because, in going around the second time the *same* sides would coincide as in going around the first time. Moreover, we can readily inscribe an equiangular polygon of an *even* number of sides which shall not be regular.

PROPOSITION XIX.

261. Theorem.—*The sides of a circumscribed equiangular polygon are equal; and the polygon is regular.*

DEM.—Let ABCDEF be a circumscribed polygon, with angle A = B = C, etc.; then is AB = BC = CD, etc., and the polygon is regular.

For, from the centre of the circle, draw OA, OB, etc., to the vertices of the polygon, and O*a*, O*b*, etc., to the points of tangency. The latter will be perpendicular to the sides by (*173*). Now reverse the triangle A*a*O, and apply it to A*b*O, placing O*a* in its equal O*b*; *a*A will take the direction *b*A. Then will OA of the triangle A*a*O, fall in OA of the triangle A*b*O, since there cannot be two equal oblique lines on the same side of O*b* (*140*). Hence *angle b*AO = *angle a*AO, and *b*A = *a*A. In the same way it can be shown that OB, OF, etc., bisect the other angles, and that *b*B = B*c*, etc. Whence, as the polygon is equiangular, these halves are equal, that is, OA*a* = OF*a*, etc. Then, as OA and OF make equal angles with AF, they cut off equal distances from *a*, and A*a* = *a*F. So, likewise, we can show that A*b* = *b*B, and that each side is bisected at the point of tangency. Therefore, as the halves of the sides are equal, the polygon is equilateral, as well as equiangular, and consequently regular (*117*). Q. E. D.

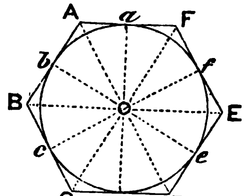

FIG. 192.

PROPOSITION XX.

262. Theorem.—*The angles of a circumscribed equilateral polygon are equal when their number is* ODD; *and the polygon is regular.*

DEM.—Let ABCDE be a circumscribed polygon with AB = BC = CD, etc.; then is *angle* A = B = C = D, etc., and the polygon is regular.

In the same manner as in the preceding demonstration, we may show that OA, OB, etc., bisect the angles of the polygon. [The student should go through the process.] Then revolve the triangle AOE upon AO as an axis till it falls in the plane of AOB; and as angle OAE = angle OAB, and AE = AB, the triangles will coincide. Hence angle OEA, the half of angle E of the polygon, equals angle OBA the half of B, and E = B. In like manner revolving AOB upon OB, we can show that A = C. So also we find B = D, and D = A. Therefore the polygon is equiangular as well as equilateral, and consequently regular. Q. E. D.

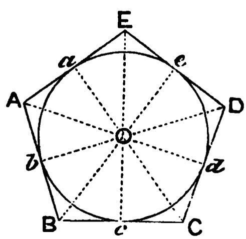

FIG. 193.

263. SCH.—That the above style of argument fails in the case of a polygon of an *even* number of sides, may be observed by attempting to apply it. Thus, from *Fig.* 192, we would have A = C, B = D, C = E, D = F, E = A, and F = B. From these we have A = C = E, and B = D = F. But the process will not give any one of the first three angles equal to any one of the second set. That is, it does not follow that two *adjacent* angles are equal in case the number of sides is *even.* We can readily construct a circumscribed equilateral polygon which shall not be equiangular.

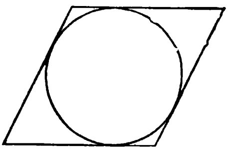

FIG. 194.

PROPOSITION XXI.

264. Theorem.—*A circumference may be circumscribed about any regular polygon.*

DEM.—Let ABCDEF be a regular polygon. Bisect AF with a perpendicular O*a*. Any point in this perpendicular is equidistant from A and F. Bisect AB, adjacent to AF, with a perpendicular, as O*b*. Any point in this perpendicular is equidistant from A and B. Hence the intersection of these perpendiculars, O, is equidistant from A, F, and B, and a circumference described from O as a centre, with a radius OA, will pass through F and B. Now revolve the quadrilateral FO*b*A upon O*b* as an axis until it falls in the plane of CO*b*B, *b*A will fall in its equal *b*B; and since angle A = angle B, and side AF = side BC, F will fall at C. Thus it appears that the circumference described from O, and passing through F, A, and B, also passes through C. In a similar manner it can be shown that the same circumference passes through all the vertices, and hence is circumscribed. Q. E. D.

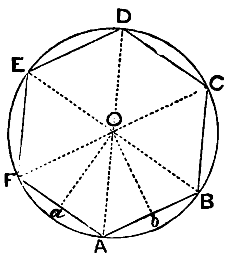

FIG. 195.

265. COR. 1.—*A circumference may be inscribed in any regular polygon.*

DEM.—For, having circumscribed one about it, the equal sides become equal chords, and hence are equally distant from the centre. If, therefore, a circle be drawn from O as a centre, with O*a* as a radius, it will touch every side of the polygon at its middle point.

266. COR. 2.—*The centres of the inscribed and circumscribed circles coincide.*

267. The Centre of a regular polygon is the common centre of its inscribed and circumscribed circles.

268. ***An Angle at the Centre*** of a regular polygon is the angle included by two lines drawn from the centre to the extremities of a side, as FOA, AOB.

269. COR. 3.—*The angles at the centre of a regular polygon are equal each to each; and any one is equal to four right angles divided by the number of sides of the polygon.*

270. ***The Apothem*** of a regular polygon is the distance from the centre to any side, and is the radius of the inscribed circle.

PROPOSITION XXII.

271. ***Theorem.***—*The side of a regular inscribed hexagon is equal to the radius.*

DEM.—Let ABCDEF be a regular inscribed hexagon; then is any side, as BC, equal to OB, the radius.

In the triangle BOC the angle O is measured by the arc BC, or $\frac{1}{6}$ of a circumference, and hence is $\frac{1}{6}$ of 4 right angles, or $\frac{2}{3}$ of a right angle. Angle ABC is measured by $\frac{1}{2}$ arc CDEFA, or $\frac{4}{6}$ of a circumference. Hence angle OBC, which is $\frac{1}{2}$ of ABC, is measured by $\frac{1}{2}$ of $\frac{2}{6}$, or $\frac{1}{6}$ of a circumference, and is, consequently, equal to BOC. So also OCB, the half of DCB, is measured by $\frac{1}{6}$ of a circumference. Hence OCB is equiangular, and consequently equilateral (*258*), and BC = OB. Q. E. D.

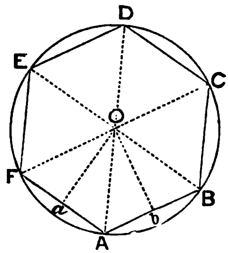

FIG. 196.

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272. A *Broken Line* is said to be *Convex* when no one of its parts will, when produced, enter the space included between it and a line joining its extremities.

PROPOSITION XXIII.

273. ***Theorem.***—*A Convex broken line is less than any broken line which envelops it and has the same extremities.*

DEM.—Let A*bcd*B be a broken line enveloped by the broken line ACDEFB, and having the same extremities A and B; then is A*bcd*B < ACDEFB.

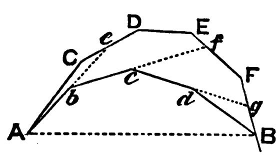


FIG. 197.

For, produce the parts of A*bcd*B till they meet the enveloping line, as A*b* to *e*, *bc* to *f*, and *cd* to *g*. Now, since a straight line is the shortest path between two points, A*e* < AC*e*, *bf* < *be*DE*f*,

$eg < cfFg$, and $dB < dgB$. Hence, if a point starts from A to move to B, AeDEFB will be a shorter path than ACDEFB, AbfFB shorter than AeDEFB, AbcgB shorter than AbfFB, and AbcdB shorter than AbcgB. Therefore, AbcdB is shorter than ACDEFB. Q. E. D.

274. COR. 1.—*The sum of any two sides of a triangle is greater than the third side.*

This is the same as the axiom that the shortest distance between two points is a straight line.

275. COR. 2.—*The difference between any two sides of a triangle is less than the third side.*

DEM.—Let a, b, and c be the sides. By Corollary 1st, $a + b > c$. Therefore, transposing, $a > c - b$.

276. COR. 3.—*If from any point within a triangle lines be drawn to the extremities of any side, the sum of these lines is less than the sum of the other two sides of the triangle.*

EXERCISES.

1. Given two angles of a triangle, to find the third.

SUG'S.—The student should draw two angles on the blackboard, as a and b, and then proceed to find the third. The figure will suggest the method. The third angle is c.

The solution is effected also by constructing the two given angles at the extremities of any line, and producing the sides till they meet.

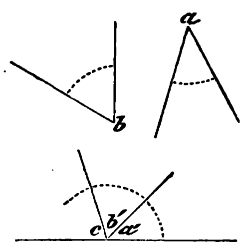


FIG. 198.

2. Two angles of a triangle are respectively $\frac{2}{3}$ and $\frac{1}{2}$ of a right angle. What is the third angle?

3. The angles of a triangle are respectively $\frac{2}{3}$, $\frac{1}{2}$, and $\frac{5}{6}$ of a right angle. Which is the greatest side? Which the least? Can you tell the ratio of the sides?

4. What is the value of one of the equal angles of an isosceles triangle whose third angle is $\frac{1}{3}$ of a right angle?

5. Two consecutive angles of a quadrilateral are respectively $\frac{4}{3}$ and $\frac{2}{3}$ of a right angle, and the other two angles are mutually equal to

each other. What is the form of the quadrilateral? What the value of each of the two latter angles?

6. One of the angles of a parallelogram is $\frac{5}{3}$ of a right angle. What are the values of the other angles?

7. The two opposite angles of a quadrilateral are respectively $\frac{2}{3}$ and $\frac{4}{3}$ of a right angle. Can a circumference be circumscribed? If so, do it.

8. Two of the opposite sides of a quadrilateral are parallel, and each is 15 in length. What is the figure? Do these facts determine the angles?

9. Two of the opposite sides of a quadrilateral are 12 each, and the other two 7 each. What do these facts determine with reference to the form of the figure?

10. What is the value of an angle of a regular dodecagon?

11. What is the sum of the angles of a nonagon? What is the value of one angle of a regular nonagon? Of one exterior angle?

12. What is the regular polygon, one of whose angles is $1\frac{13}{17}$ right angles?

13. What is the regular polygon, one of whose exterior angles is $\frac{2}{3}$ of a right angle?

14. Can you cover a plane surface with equilateral triangles without overlapping them or leaving vacant spaces? With quadrilaterals? Of what form? With pentagons? Why? With hexagons? Why? What insect puts the latter fact to practical use? Can you cover a plane surface thus with regular polygons of more than 6 sides? Why?

15. Is an equilateral hexagon circumscribed about a circle necessarily regular? A heptagon? An octagon? A nonagon?

16. Is an equiangular circumscribed quadrilateral necessarily regular? A pentagon? A hexagon? A heptagon?

17. Is an equilateral inscribed pentagon necessarily regular? An octagon? How is it if they are equiangular; are they necessarily equilateral and regular?

SYNOPSIS.

- **ANGLES AND SIDES OF POLYGONS.**
  - **TRIANGLES.**
    - PROP. I. Sum of angles.
      - *Cor.* 1. Only one right or obtuse.
      - *Cor.* 2. Two angles given.
      - *Cor.* 3. Acute angles if right angled
      - *Cor.* 4. One angle if equiangular.
    - PROP. II. Sides and opp. angles.
      - *Cor.* 1. Converse.
      - *Cor.* 2. Equiangular, equilateral, and converse.
      - *Cor.* 3. Isosceles, equiangular, and converse.
      - *Sch.* These only general relations.
    - PROP. III. Angle within a triangle.
    - DEF. Exterior angle.
    - PROP. IV. Exterior angle.—*Cor.* Non-adjacent interior.
  - **QUADRILATERALS.**
    - PROP. V. Sum of angles.
    - PROP. VI. Angles of inscribed.
    - **PARALLELOGRAMS.**
      - PROP. VII. Angles of.
        - *Cor.* 1. Of a trapezoid.
        - *Cor.* 2. Of a rectangle.
      - PROP. VIII. Converse to last.
      - PROP. IX. Two op. sides of a quadrilat'l equal and parallel.
      - PROP. X. Opposite sides of a quadrilateral equal.
      - PROP. XI. Converse to last.
        - *Cor.* 1. Parallels intercepted bet. parallels.
        - *Cor.* 2. Diagonal of a parallelogram.
      - DIAGONALS.
        - PROP. XII. Bisect.
        - PROP. XIII. Of a rhombus.—*Cor.* Bisect angles.
        - PROP. XIV. Of a rectangle.—*Cor.* Converse.
  - **POLYGONS OF MORE THAN 4 SIDES.**
    - DEF'S.—Salient angle.—Re-entrant.—Convex polygon.—Concave.
    - PROP. XV. Sum of angles.
      - *Sch.* 1. Application.
      - *Sch.* 2. Applied to triangles.
      - *Sch.* 3. Angle of equiangular polygon.
    - PROP. XVI. Sum of exterior angles.
    - REGULAR.
      - PROP. XVII. Equilateral inscribed, regular.
      - PROP. XVIII. Equiangular inscribed if odd No. of sides.
        - *Sch.* Fails for even No.
      - PROP. XIX. Equiangular circumscribed, regular.
      - PROP. XX. Equilateral circbd. if odd No. of sides.
        - *Sch.* Fails for even No.
      - PROP. XXI. Circf. can be circumscribed.
        - *Cor.* 1. Inscribed.
        - *Cor.* 2. Centres.
        - *Def.* Angle at cntr.
        - *Cor.* 3. Value of angle at centre.
        - *Def.* Apothem.
      - PROP. XXII. Side of inscribed hexagon.
  - DEF. Convex Broken Line.
  - PROP. XXIII. Convex broken line < than —.
    - *Cor.* 1. Sum of two sides of triangle.
    - *Cor.* 2. Diff. of two sides of triangle.
    - *Cor.* 3. Lines from point within triangle.
  - EXERCISES.

SECTION VIII.

OF EQUALITY.

277. *Equality* signifies likeness in every respect.

278. The equality of magnitudes is usually shown by applying one to the other, and observing that they coincide.

PROPOSITION I.

279. *Theorem.*—*Two straight lines of the same length are equal magnitudes.**

DEM.—Let AB and CD be two straight lines of the same length; then are they equal.

For, conceive the extremity C of CD placed at A, and the other extremity somewhere in AB, or in AB produced, as the case may be. Now, the point which traces AB passes through all points in the direction of B from A; and hence, if CD is traced from A towards B, it will pass through the same points as far as they mutually extend. The lines therefore coincide, as far as they both extend; and, being of the same length, D falls at B, and they coincide throughout; they are, therefore, equal. Q. E. D.

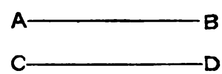


FIG. 198.*

ILL.—The truth of this theorem is so evident, that the student may fail to see the point of the demonstration. Let him see if he can say the same things of two curved lines A*m*B, and C*n*D, which are of the same length.

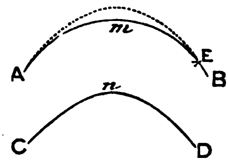


FIG. 199.

The substance of the demonstration is as follows: A line has two properties, and *only* two, *form* and *magnitude*. *Straight* lines, being of the same form, if they are of the same magnitude, are alike in all respects; *i. e.*, they are equal. Now, a line, as a magnitude, has only one dimension, viz., length. If, therefore, two lines have the same length, they have the same magnitude.

* See Preface.

PROPOSITION II.

280. *Theorem.*—*Two circles whose radii are of the same length are equal;* i. e., *the circumferences are equal, and the circles equal.*

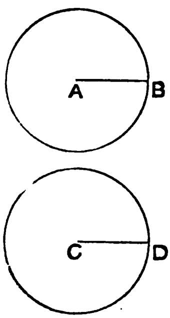


FIG. 200.

DEM.—Let there be two circles whose radii AB and CD are of the same length; then are the circles equal.

For, place the second circle on the first, with the centre C at A, and CD in AB. As CD = AB, D will fall at B. Now, every point in the plane at a distance AB from A is in the circumference of circle A. But every point at a distance CD from the common centre is in the circumference of circle C. Hence, the two figures coincide, and the circles are alike in all respects, *i. e.*, are equal. Q. E. D.

OF ANGLES.

PROPOSITION III.

281. *Theorem.*—*Two angles whose sides are parallel, two and two, and lie in the same or in opposite directions from their vertices, are equal.*

DEM.—1st. In (*a*) or (*a'*) let B and E have BA and ED parallel, and extending in the same direction from the vertices, and also BC and EF; then are B and E equal. For, produce (if necessary) either two sides which are not parallel, till they intersect, as at H; then are the corresponding angles DHC and DEF, and DHC and ABC equal (*152*). Hence, ABC = DEF.

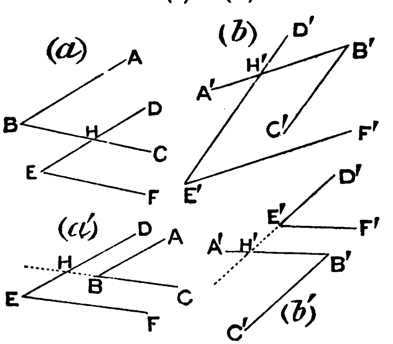


FIG. 201.

2nd. In (*b*) and (*b'*) let B' and E' have B'A' parallel with E'F', but extending in an opposite direction from its vertex; and in like manner B'C' parallel with, but extending in an opposite direction from E'D'; then are B' and E' equal. For, produce (if necessary) two of the sides which are not parallel till they intersect, as at H'; then D'H'B' = the corresponding angle D'E'F', and also = the alternate interior angle A'B'C'; whence A'B'C' = D'E'F'. Q. E. D.

PROPOSITION IV.

282. Theorem.—*If two angles have two sides parallel and extending in the same direction with each other, while the other two sides are parallel and extend in opposite directions from each other, the angles are supplemental.*

DEM.—Let ABC and DEF be two angles, having BC and ED parallel, and extending in the same direction from the vertices, and AB and EF parallel, and extending in opposite directions from the vertices; then are ABC and DEF supplements of each other.

For, produce the two sides not parallel, if necessary, till they meet. Now, BHD is the supplement of BHE by (*131*), BHE = the alternate interior angle DEF, and BHD = the corresponding angle ABC. Therefore, ABC is the supplement of DEF. Q. E. D.

[This demonstration is adapted to the upper cut; let the student adapt it to the lower.]

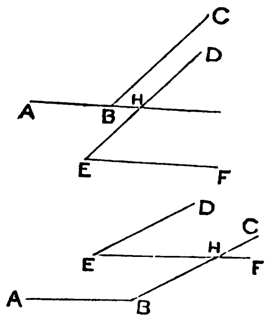


FIG. 202.

PROPOSITION V.

283. Theorem.—*If two angles have their sides respectively perpendicular to each other, the angles are either equal or supplementary.*

DEM.—Let BA be perpendicular to EF or to E′F′, and BC to ED; then is ABC = DEF. For, through B draw BO and BN, respectively parallel to ED and EF; then by the preceding propositions NBO = DEF, and is the supplement of F′E′D. But NBA = OBC, since both are right angles. Take away OBA from each, and we have NBO = ABC; and as NBO is the supplement of F′E′D, ABC is also the supplement of F′E′D. Q. E. D.

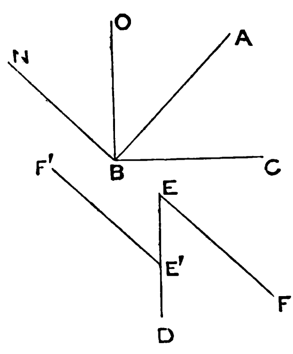


FIG. 203.

OF TRIANGLES.

PROPOSITION VI.

284. Theorem.—*Two triangles which have two sides and the included angle of one equal to two sides and the included angle of the other, each to each, are equal.*

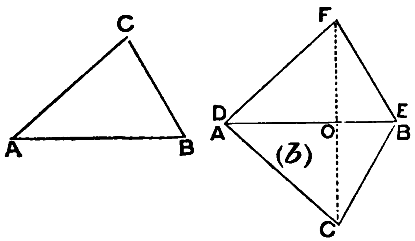


FIG. 204.

DEM.—Let ABC and DEF be two triangles, having AC = DF, AB = DE, and angle A = angle D; then are the triangles equal.

For, place the triangle ABC in the position (*b*), the side AB in its equal DE, and the angle A adjacent to its equal angle D. Then revolving ABC upon DB, until it falls in the plane on the opposite side of DB, since angle A = angle D, AC will take the direction DF; and as AC = DF, C will fall at F. Hence BC will fall in EF, and the triangles will coincide. Therefore the two triangles are equal. Q. E. D.

We may also make the application of ABC to DEF directly, as in (*85*). The method here given is used for the purpose of uniformity in this and the following. We may observe that in this, as in the other cases, DB is perpendicular to FC, and bisects it at O. This fact might easily be shown, and the demonstration be based upon it.

285. SCH.—This proposition signifies that the two triangles *are equal in all respects, i. e.*, that the two remaining sides are equal, as CB = FE; that angle C = angle F, angle B = angle E, and that the areas are equal.

PROPOSITION VII.

286. Theorem.—*Two triangles which have two angles and the included side of the one equal to two angles and the included side of the other, each to each, are equal.*

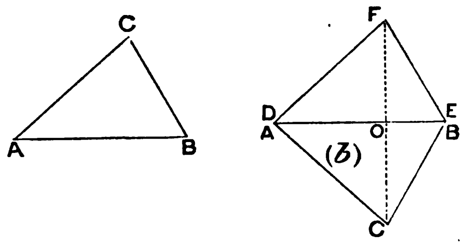


FIG. 205.

DEM.—Let ABC and DEF be two triangles, having angle A = angle D, angle B = angle E, and side AB = side DE; then are the triangles equal.

For, place ABC in the position (*b*), the side AB in its equal DE, the angle A adjacent to its equal angle D, and B adjacent to its equal angle E. Then revolving ABC upon DB till it falls in the plane on the same side as DFE, since angle A = angle D, AC will take the direction DF, and C will fall somewhere in DF or DF produced. Also, since angle B = angle E, BC will take the direction EF, and C will fall somewhere in EF, or EF produced. Hence, as C falls at the same time in DF and EF, it falls at their intersection F. Therefore the two triangles coincide, and are consequently equal. Q. E. D.

287. COR.—*If one triangle has a side, its opposite angle, and one adjacent angle, equal to the corresponding parts in another triangle, each to each, the triangles are equal.*

For the third angle in each is the supplement of the sum of the given angles, and they are consequently equal. Whence the case is included in the proposition.

288. SCH.—A triangle may have a side and one adjacent angle equal to a side and an adjacent angle in another, and the second adjacent angle of the first equal to the angle *opposite* the equal side in the second, and the triangles *not* be equal. Thus, in the figure, AB = C′A′, A = A′, and B = B′; but the triangles are evidently not equal. [Such triangles are, however, *similar*, as will be shown hereafter.]

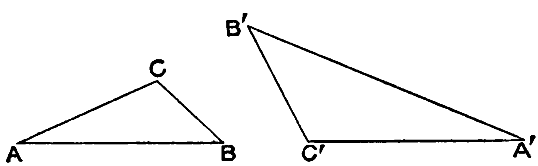


FIG. 206.

PROPOSITION VIII.

289. ***Theorem.***—*Two triangles which have two sides and an angle opposite one of these sides, in the one, equal to the corresponding*

parts in the other, are equal, if of these two sides the one opposite the given angle is equal to or greater than the one adjacent.

DEM.—In the triangles ABC and DEF, let AC = DF, CB = FE, A = D, and CB (= FE) $\overline{>}$ AC (= DF); then are the triangles equal.

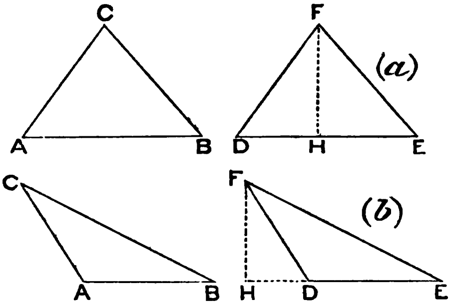


FIG. 207.

For, apply AC to its equal DF, the point A falling at D and C at F. Since A = D, AB will take the direction DE. Let fall the perpendicular FH upon DE, or DE produced. Now, CB being $\overline{>}$ DF, cannot fall between it and the perpendicular, but must fall in FD or beyond both. As there can be but one line on the same side of the perpendicular equal to CB, and as FE = CB, CB must fall in FE. Hence, the two triangles coincide, and are consequently equal. Q. E. D.

290. SCH. 1.—If A and D are acute and CB (= FE) = AC (= DF), the triangles are isosceles. If A and D are right or obtuse, CB (=FE) must be *greater* than AC (= DF), in order that there may be a triangle, since the right or obtuse angle is the greatest angle in a triangle, and the greatest side is opposite the greatest angle. This impossibility appears also from the demonstration above.

291. SCH. 2.—If A and D are *acute*, and the side opposite A, *i. e.*, CB, is less than AC, it must be equal to or greater than the perpendicular CI (= FH) in order to have a triangle. Then, applying AC to DF, and observing that AB takes the direction DE, and that EF, which = CB, being intermediate in length between DF and FH, may lie on either side of FH, we see that ABC may or may not coincide with DEF. Whether it does or not will depend upon whether angle C = angle F, or whether AB = DE. This is the AMBIGUOUS CASE in the solution of triangles, and should receive special attention.

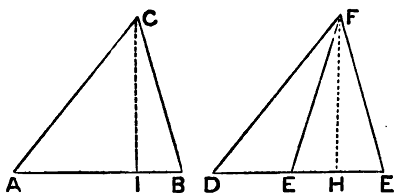


FIG. 208.

PROPOSITION IX.

292. Theorem.—*Two triangles which have the three sides of the one equal to the three sides of the other, each to each, are equal.*

DEM.—Let ABC and DEF be two triangles, in which AB = DE, AC = DF, and BC = EF; then are the triangles equal.

For, place the triangle ABC in the position (*b*), and the side AB in its equal DE, so that the other equal sides shall be adjacent, as AC adjacent to DF, and BC to EF. Draw FC. Now, since DC = DF, and EC = EF, DB is perpendicular to FC at its middle point (*130*). Hence, revolving ABC upon DB, it will coincide with DEF when brought into the plane of the latter Therefore the two triangles are equal. Q. E. D.

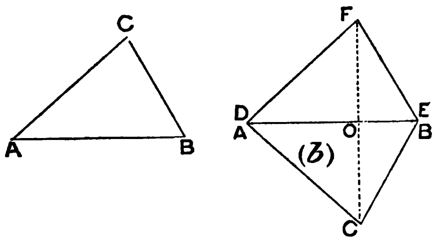


FIG. 209.

293. COR.—*In two equal triangles, the equal angles lie opposite the equal sides.*

294. SCH.—If the triangles compared, as in the three preceding propositions, have an obtuse angle, and the two sides first brought together are sides about the obtuse angle, the figure will take the form in the margin; but the demonstration will be the same. When the three sides are the given equal parts, the form of figure given in the demonstration above can always be secured by bringing together the two *greatest* sides.

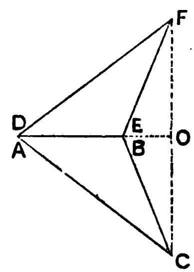


FIG. 210.

PROPOSITION X.

295. Theorem.—*If two triangles have two sides of the one respectively equal to two sides of the other, and the included angles unequal, the third sides are unequal, and the greater third side belongs to the triangle having the greater included angle.*

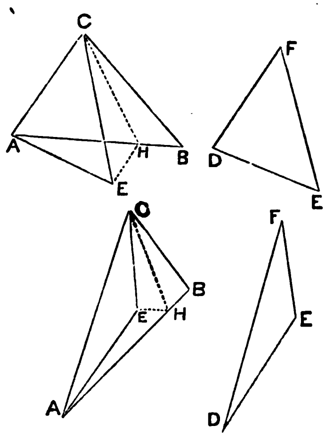


Fig. 211.

Dem.—Let ACB and DEF be two triangles having AC = DF, CB = FE, and C > F; then is AB > DE.

For, placing the side DF in its equal AC, since angle F < angle C, FE will fall within the angle ACB, as in CE. Then let the triangle ACE = the triangle DFE. Bisect ECB with CH, and draw HE. The triangles HCB and HCE have two sides and the included angle of the one, respectively equal to the corresponding parts of the other, whence HE = HB. Now AH + HE > AE; but AH + HE = AH + HB = AB. Therefore, AB > AE. Q. E. D.

296. Cor. — Conversely, *If two sides of one triangle are respectively equal to two sides of another, and the third sides unequal, the angle opposite this third side is the greater in the triangle which has the greater third side.*

Dem.—If AC = DF, CB = FE, and AB > DE, angle C > angle F. For, if C = F, the triangles would be equal, and AB = DE (***284***); and, if C were less than F, AB would be less than DE, by the proposition. But both these conclusions are contrary to the hypothesis. Hence, as C cannot be equal to F, nor less than F, it must be greater.

PROPOSITION XI.

297. Theorem.—*Two right angled triangles which have the hypotenuse and one side of the one equal to the hypotenuse and one side of the other, each to each, are equal.*

Dem.—In the two triangles ABC and DEF, right angled at B and E, let AC = DF, and BC = EF; then are the triangles equal.

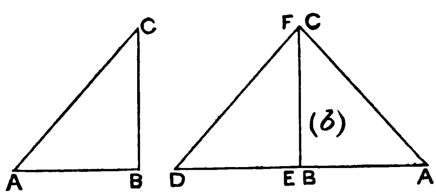


Fig. 212.

For, place BC in its equal EF, so that the right angles shall be adjacent, the angles A and D lying on opposite sides of EF, as in (*b*). Since E and B are right angles, DA is a straight line. Now, since equal oblique lines, as FD and CA, cut off equal distances from the foot of the perpendicular (***141***), DE = BA; and revolving CAB upon FB, the two

triangles will coincide when CAB falls in the plane on the side D. Therefore, the triangles are equal. Q. E. D.

PROPOSITION XII.

298. Theorem.—*Two right angled triangles having the hypotenuse and one acute angle of the one equal to the hypotenuse and an acute angle of the other, are equal.*

DEM.—One acute angle in each being equal, the other acute angles are equal, since they are complements of the same angle (*222*). The case is, then, that of two angles (the acute angles in each), and their included side (the hypotenuse), and falls under (*286*).

PROPOSITION XIII.

299. Theorem.—*Two right angled triangles having a side and one acute angle in each equal, are equal.*

This also falls under (*286*). Let the student show why.

OF QUADRILATERALS.

PROPOSITION XIV.

300. Theorem.—*Two quadrilaterals having three sides of the one equal to the three corresponding sides of the other, each to each, and the two corresponding angles adjacent to the unknown sides equal, each to each, are equal figures.*

DEM.—In Q and Q′ let AB = A′B′, AD = A′D′, DC = D′C′, B = B′, and C = C′; then are the quadrilaterals equal.

For, from the extremities of the side opposite the unknown side, in each, let fall perpendiculars upon the unknown side, or this side produced, as A*f*, D*e*, and A′*f*′, D′*e*′. Now, the right angled triangles AB*f* and A′B′*f*′ have the hypotenuse and one acute angle in the one equal to the corresponding parts in the other, whence they are equal, and

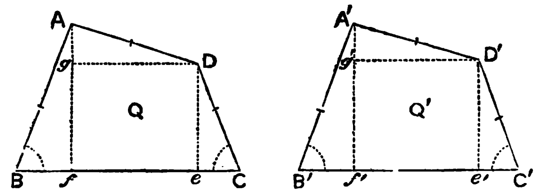


FIG. 213.

$Af = A'f'$. In like manner $De = D'e'$. Drawing Dg, and $D'g'$ parallel to BC and B'C', respectively, we have $Ag = A'g'$. Hence, the right angled triangles AgD and $A'g'D'$, as they have the hypotenuse and one side in the one equal to the corresponding parts in the other, are equal. Finally, the angles A and A' are made up respectively of the equal parts BAf and gAD, and $B'A'f'$ and $g'A'D'$, and are consequently equal. So also $D = D'$, and the quadrilaterals are equal in all their parts, and can be applied so as to coincide.

PROPOSITION XV.

301. Theorem.—*Two parallelograms having two sides and the included angle of the one equal to two sides and the included angle of the other, each to each, are equal.*

DEM.—Let AC and EG be two parallelograms, with $AD = EH$, $AB = EF$, and $A = E$; then are they equal.

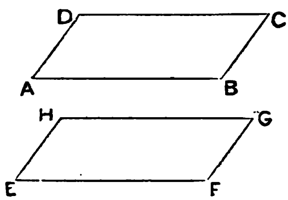


FIG. 214.

For, applying the angle E to A, since $EH = AD$, H will fall at D; and since $EF = AB$, F will fall at B. Now, through D but one line can be drawn parallel to AB; hence HG will fall in DC, and G will be found in DC, or in DC produced. In like manner, since but one parallel to AD can be drawn through B, FG must fall in BC, and G be found in BC, or in BC produced. Therefore, as G falls at the same time in DC and BC, it falls at C, and the parallelograms coincide.

302. COR.—*Two rectangles of the same base and altitude are equal.*

OF POLYGONS.

PROPOSITION XVI.

303. Theorem.—*Two polygons of the same number of sides, having all the parts of the one except three angles respectively equal to the corresponding parts of the other, are equal.*

DEM.—If the two polygons AE* and A'E', have all the parts of the one equal to the corresponding parts of the other, each to each, except three angles; then are the polygons equal.

* It is often more convenient to read a polygon by two letters, instead of all those at the vertices.

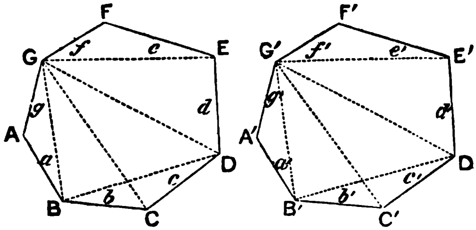


FIG. 215.

1st. When the three unknown angles are consecutive, as C, F, E, and C′, F′, E′. Draw CE, and C′E′. Apply polygon A′E′ to AE, beginning with g' in its equal g: A′ = A, and $a' = a$; hence, B′ falls at B; B′ = B, and $b' = b$, hence, C′ falls at C; etc. Thus, we may show that the perimeters coincide till we reach E′ and E. Then will C′E′ = CE, and the triangles CFE and C′F′E′, having their corresponding sides respectively equal, are themselves equal, and the polygons coincide throughout.

2d. When two of the unknown angles are consecutive, and the third not consecutive with these, as C, E, D, and C′, E′, D′. From the angle which is not consecutive with the other two, draw diagonals to the other angles, as CE, CD, and C′E′, C′D′. Now, C′A′B′C′D′ can be applied to CABCD, and C′F′E′ to CFE, in the ordinary way. Hence, the triangles C′E′D′ and CED are mutually equilateral, and consequently equal. Therefore the polygons are equal.

3d. When no two of the three unknown angles are consecutive, as C, B, D, and C′, B′, D′. Join the unknown angles by diagonals, as CB, CD, BD, and C′B′, C′D′, B′D′. Now, polygon C′F′E′D′ can be applied to CFED, D′C′B′ to DCB, and C′A′B′ to CAB in the ordinary way. Hence, the triangles C′D′B′ and CDB are mutually equilateral, and consequently equal. Therefore the polygons are equal.*

304. COR.—*Two quadrilaterals having their corresponding sides equal, and an angle in one equal to the corresponding angle in the other, are equal.*

PROPOSITION XVII.

305. Theorem.—*Two polygons of the same number of sides, having all the parts of the one except two angles and one side, respectively equal to the corresponding parts of the other, are equal, if both unknown angles are adjacent to the unknown side, or both are separated from it.*

DEM.—1st. When the unknown angles are adjacent to the unknown side, as C, c, D, and C′, c', D′. From any other two of the mutually equal angles, as C

* Notice that in each case the unknown angles are to form the vertices of triangles, which the argum nt shows to be equilateral, and therefore equal. In Case 1st, we have to draw only one line in order to give the triangles, as two sides are sides of the polygon; in Case 2d, we have to draw two sides; and in Case 3d, three sides, for analogous reasons.

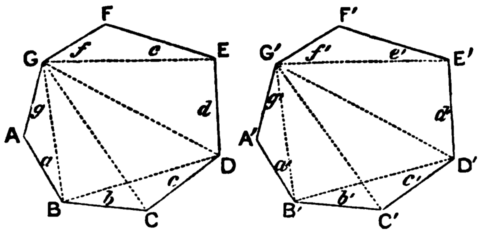


FIG. 216.

and C′, draw the diagonals GC, GD, G′C′, G′D′, to the unknown angles. Then the polygon G′F′E′D′ can be applied in the ordinary way to GFED, f' being placed in f, etc. So also G′A′B′C′ can be applied to GABC, beginning with g' in its equal g. Hence, angle F′G′D′ = FGD, A′G′C′ = AGC; and, adding, F′G′D′ + A′G′C′ = FGD + AGC. Subtracting these equals from G′ = G, we have C′G′D′ = CGD. Whence the triangles C′G′D′ and CGD have two sides and their included angle equal in each, and are equal; therefore the polygons are equal in all their parts.

2d. When the unknown angles are both separated from the unknown side.

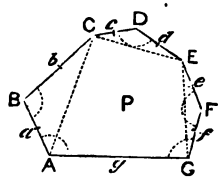


FIG. 217.

Let P be one of the polygons, and P′ (the student should draw P′) be the other. Let g, C, and E, and the corresponding parts in P′, be the unknown parts. Join the unknown angles with each other, and with the extremities of the unknown side, as by CE, CA, and EG. Now the polygons ABC, CDE, and EFG, are equal respectively to the corresponding polygons of P′. Hence, the quadrilateral ACEG has AC, CE, EG, and its angles A and G equal to the corresponding parts of the quadrilateral in P′. These quadrilaterals are therefore equal (*300*), and the polygons are equal in all their parts. Q. E. D.

306. SCH.—When one of the unknown angles is adjacent to the unknown side and the other separated, the polygons may or may not be equal. Thus, let

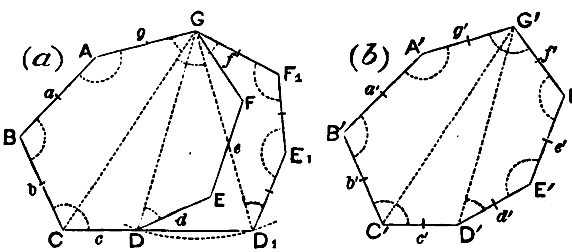


FIG. 218.

the unknown parts be D, c, G, and D′, c', G′. From the separated angle draw the diagonals to the extremities of the unknown side, as GC, GD (or GD₁), and G′C′, G′D′. In the usual way G′A′B′C′ can be applied to GABC, and G′F′E′D′ to

CFED. Whence C'C' = GC, G'D' = GD, and angle G'C'D' = GCD. Thus the case is reduced to that of two triangles having two sides and an angle opposite one of them mutually equal, and is, therefore, ambiguous. The polygon (*a*) may have the part corresponding to C'F'E'D' situated as CFED, or as $CF_1E_1D_1$. In the former case the polygons are equal, in the latter not.

307. Cor.—*Two quadrilaterals having three sides and the corresponding angles included by these sides equal, are equal.*

This falls under the 1st case.

308. Sch.—If the three unknown or excepted parts are all sides, the polygons are not necessarily equal, as will appear by an inspection of the figure. The

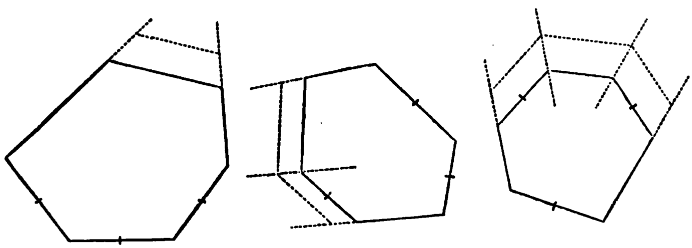


Fig. 219.

unmarked sides being the excepted ones, the polygons may be those included by the continuous lines, or those included in part by the broken lines, all the parts being equal in each two, except the three unknown ones.

PROPOSITION XVIII.

309. Theorem.—*Two polygons of the same number of sides, having two adjacent sides and the diagonals drawn from the included angle, in the one, respectively equal to the corresponding parts in the other, and their corresponding included angles equal, are equal figures.*

Dem.—The demonstration is based upon (*284*). Let the student draw the figures, and make the applications.

PROPOSITION XIX.

310. Theorem.—*Two polygons of the same number of sides, having all the parts (sides and angles) of the one respectively equal to the corresponding parts of the other, except two parts, are equal, unless the excepted parts are parallel sides.*

DEM.—The demonstration can be supplied by the pupil, as it is similar to the several preceding. The cases will be, 1st, When two angles are excepted, (*a*) they being consecutive, (*b*) they not being consecutive;—2d, An angle and a side, (*a*) consecutive, (*b*) not consecutive;—3d, Two sides, (*a*) consecutive, (*b*) not consecutive.

EXERCISES.

1. ***Prob.****—Having two sides and their included angle given, to construct a triangle.*

SUG'S.—The student should draw two lines on the blackboard, and a detached angle, as the given parts. Then, making an angle equal to the given angle (***200***), he should lay off the given sides from the vertex on the sides of the angle, and join their extremities. The triangle thus formed is the one required, for any other triangle formed with these two sides and this angle will be just like this by (***284***).

2. ***Prob.****—Having two angles and their included side given, to construct a triangle.*

3. ***Prob.****—Having the three sides of a triangle given, to construct the triangle.*

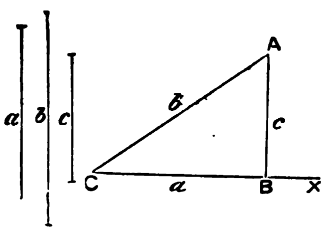
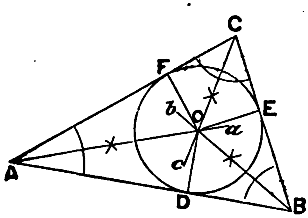


FIG. 220.

SOLUTION.—Let *a*, *b*, and *c*, be the given sides. Draw an indefinite line CX, and on it take CB = *a*. From C as a centre with *b* as a radius, describe an arc as near as can be discerned where the angle A will fall. From B, with a radius *c*, describe an arc intersecting the former. Then is ABC the triangle required, since any other triangle having the same sides would be equal to ABC (***292***).

4. ***Prob.****—To inscribe a circle in a given triangle.*

SOLUTION.—For the method of doing it see PART I. (***79***). To prove the method correct, we observe that the triangles ODB and OBE have OB common, and are mutually equiangular; hence they are equal, and OD = OE. In like manner triangle OEC = OFC, and OE = OF. [Triangle OFA = ODA; but we do not need the fact in the demonstration.] Since OD = OE = OF, the circumference struck from O as a centre with a radius OD, passes through E and F. Moreover, since each side of the triangle is perpendicular to a radius at its extremity, it is tangent to the circle (***172***); and the circle is inscribed.



5. ***Prob.***—*Having two sides and an angle opposite one of them given, to construct the triangle.*

SOLUTION.—1st. When the given angle is right or obtuse, the side opposite must be greater than the side adjacent, as the greatest side is opposite the greatest angle (*224*), and the greatest angle in such a triangle is the right or

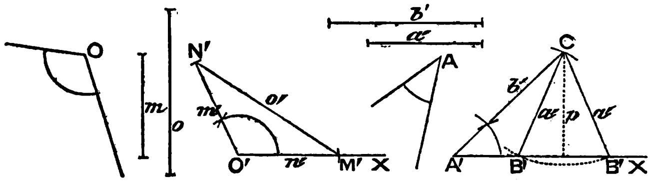


FIG. 221.

obtuse angle. In this case let m and o be the given sides, and O the angle opposite o. Draw an indefinite line O′X, construct O′ equal to O, and take O′N′ equal to m. From N′ as a centre, with a radius equal to O, describe an arc cutting O′X, as at M′. Draw N′M′. Then is N′M′O′ the triangle required, since all triangles having their corresponding parts equal to m', o', and O′ are equal.

2d. When the given angle is acute, as A, there will be *no solution* if the given side, a, opposite A, is less than the perpendicular; *one solution* if $a = p$, or if $a >$ than both p and b, and *two solutions* if $a > p$, and less than b. This will appear from the construction, which is the same as in Case 1st.

6. If a perpendicular be let fall from the right angle C of the triangle ACD, upon the hypotenuse, as CD, show from (*222*) that the three triangles in the figure are mutually equiangular.

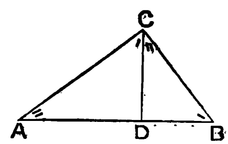


FIG. 222.

7. Given the sides of a triangle, as 15, 8, and 5, to construct the triangle.

8. Given two sides of a triangle $a = 20$, $b = 8$, and the angle B opposite the side b equal $\frac{1}{3}$ of a right angle,* to construct the triangle.

9. Same as in the 8th, except $b = 12$. Same, except that $b = 25$.

10. Construct a triangle with angle A $= \frac{2}{3}$ of a right angle, angle B $= \frac{1}{2}$ of a right angle, and side a opposite angle A, 15.

11. Construct a right angled triangle whose hypotenuse is 16, and

* To construct this angle, bisect an angle of an equilateral triangle.

one of the other sides 7. The same with one acute angle $\frac{2}{3}$ of a right angle, and a side about the right angle 12. Will there be any difference in the *shape* of the triangles if one is constructed with the given angle adjacent to the given side, and the other with it opposite? Will there be any difference in the *size*?

12. Construct a right angled triangle having its hypotenuse 20, and one acute angle $\frac{1}{3}$ of a right angle.

13. Construct a quadrilateral three of whose sides are 20, 12, and 15, and the angle included between 20 and the unknown side $\frac{2}{3}$ of a right angle, and that between 15 and the unknown side $\frac{1}{2}$ a right angle.

SUG'S.—Make A = $\frac{2}{3}$ of a right angle, and $b = 20$. From D as a centre, with a radius 12, strike the arc *on*. At any point on side a, make an angle B′ = $\frac{1}{3}$ a right angle. Take B′m = 15, and draw Cm parallel to AB′. From the intersection C draw CB parallel to mB′. Draw CD. Then is ABCD the quadrilateral required.

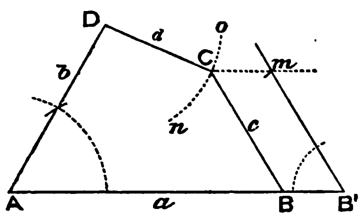


FIG. 223.

Queries.—If $d + c$ is less than the perpendicular from D upon AB, then what? If equal to the perpendicular, then what? Is it necessary to consider angle B in answering the two preceding queries?

14. Construct a parallelogram whose two adjacent sides are 6 and 8, and whose included angle equals $1\frac{1}{3}$ right angles.

15. Construct a heptagon whose sides in order are $a = 4$, $b = 5$, $c = 5$, $d = 6$, $e = 6$, $f = 3$, $g = 4$; and the angle included between a and b, $1\frac{1}{2}$ right angles; between b and c, $1\frac{2}{3}$; c and d, $1\frac{1}{3}$; d and e, $1\frac{1}{4}$.

SUG'S.—See *Fig.* 187. Proceed in order, laying off the parts as given, from A to F. Draw AF. From F as a centre, with a radius $f = 3$, strike an arc, and also from A, with a radius $g = 4$. The intersection of these arcs will determine G.

Queries.—What is the limit of the sum of the possible values of the given angles? What the limit of the sum of the sides included between the unknown angles?

SYNOPSIS.

- **Of Equality.**
  - What? How shown?
  - Prop. I. Of straight lines.
  - Prop. II. Of circles.
  - **Angles.**
    - Prop. III. Sides parallel. Direction same or opposite.
    - Prop. IV. " " " one same, other opposite.
    - Prop. V. " perpendicular.
  - **Triangles.**
    - Prop. VI. Two sides and included angle.
      - *Sch.* All parts equal.
    - Prop. VII. Two angles and included side.
      - *Cor.* Side, one adjacent and one opposite angle equal.
      - *Sch.* Exception.
    - Prop. VIII. Two sides and angle opposite one.
      - *Sch.* 1. When isosceles.
      - *Sch.* 2. When ambiguous.
    - Prop. IX. Three sides.
      - *Cor.* Equal angles opposite equal sides.
      - *Sch.* Case of obtuse angle. Form of *Fig.*
    - Prop. X. Two sides equal. included angles unequal.
      - *Cor.* Converse.
    - **Right Angled.**
      - Prop. XI. Hypotenuse and one side.
      - Prop. XII. Hypotenuse and one acute angle.
      - Prop. XIII. Side and one acute angle.
  - **Quadrilaterals.**
    - Prop. XIV. Three sides and non-included angles equal.
    - Prop. XV. Two parallelograms having two sides and the included angles equal.
      - *Cor.* Rectangles of same base and altitude.
  - **Polygons of more than 4 Sides.**
    - Prop. XVI. Three angles excepted.
      - *Cor.* Quadrilaterals.
    - Prop. XVII. Two angles and one side excepted.
      - *Sch.* 1. The ambiguous case.
      - *Cor.* Quadrilaterals.
      - *Sch.* 2. Three sides excepted.
    - Prop. XVIII. Two sides and included diagonals.
    - Prop. XIX. Any two parts excepted.
  - **Exercises.**
    - *Prob.* In a triangle, given two sides and included angle.
    - *Prob.* " " " angles " side.
    - *Prob.* " " " sides and angle opposite one.
    - *Prob.* " " " three sides.
    - *Prob.* To inscribe a circle in a triangle.

SECTION IX.

OF EQUIVALENCY AND AREA.

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311. *Equivalent Figures* are such as are equal in magnitude.

PROPOSITION I.

312. *Theorem.*—*Parallelograms having equal bases and equal altitudes are equivalent.*

DEM.—Let ABCD and EFGH be two parallelograms having equal bases, BC and FG, and equal altitudes; then are they equivalent.

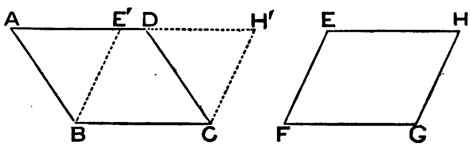

FIG. 223 *

For, place FG in its equal BC; and, since the altitudes are equal, the upper base EH will fall in AD or AD produced, as E′H′. Now, the two triangles AE′B and DH′C are equal, because the three sides of the one are respectively equal to the three sides of the other. Thus AB = DC, being opposite sides of the same parallelogram. For a like reason, E′B = H′C. Also, E′H′ = BC = AD. From AH′ taking E′H′, AE′ remains, and taking AD, DH′ remains. Therefore AE′ = DH′. These triangles being equal, the quadrilateral ABCH′ − the triangle AE′B = ABCH′ − DH′C. But ABCH′ − AE′B = E′BCH′ = EFGH; and ABCH′ − DH′C = ABCD. Hence, ABCD = EFGH. Q. E. D.

313. COR.—*Any parallelogram is equivalent to a rectangle having the same base and altitude.*

PROPOSITION II.

314. *Theorem.*—*A triangle is equivalent to one-half of any parallelogram having an equal base and an equal altitude with the triangle.*

DEM.—Let ABC be a triangle. Through C draw CD parallel to AB; and through A draw AD parallel to BC. Then is ABCD a parallelogram, of which ABC is one-half (*243*). Now, as any other parallelogram having an equal base and altitude with ABCD is equivalent to ABCD (*312*), ABC is equivalent to one-half of *any* parallelogram having an equal base and altitude with ABC. Q. E. D.

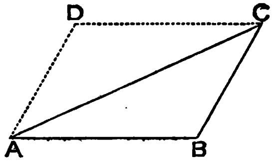

FIG. 224.

315. COR. 1.—*A triangle is equivalent to one-half of a rectangle having an equal base and an equal altitude with the triangle.*

316. COR. 2.—*Triangles of equal bases and equal altitudes are equivalent,* for they are halves of equivalent parallelograms.

PROPOSITION III.

317. Theorem.—*The square described on a line is equivalent to four times the square described on half the line, nine times the square described on one-third the line, sixteen times the square on one-fourth the line,* etc.

DEM.—Let AB be any line. Upon it describe the square ABCD. Bisect AB, as at *d*, and AD, as at *a*. Draw *dc* parallel to AD, and *ab* parallel to AB. Now, the four quadrilaterals thus formed are parallelograms by construction, hence their opposite sides and angles are equal; and as A, B, C, and D are right angles, and A*a* = A*d* = *d*B = *b*B = etc., the four figures 1, 2, 3, 4, are equal squares. Hence A*doa* = ¼ ABCD. In like manner it can be shown that the nine figures into which the square on A′B′ is divided by drawing through the points of trisection of the sides, lines parallel to the other sides, are equal squares. Hence A′*o*′, the square on ⅓ of A′B′, is $\frac{1}{9}$ of the square A′B′C′D′. The same process of reasoning can be extended at pleasure, showing that the square on ¼ a line is $\frac{1}{16}$ the square of the whole, etc.

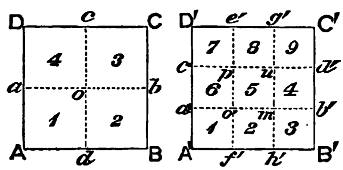

FIG. 225.

PROPOSITION IV.

318. Theorem.—*A trapezoid is equivalent to two triangles having for their bases the upper and lower bases of the trapezoid, and for their common altitude the altitude of the trapezoid.*

DEM.—By constructing any trapezoid, and drawing either diagonal, the student can show the truth of this theorem.

PROPOSITION V.

319. Prob.—*To reduce any polygon to an equivalent triangle.*

SOLUTION.—Let ABCDEF be a polygon which it is proposed to reduce to an equivalent triangle. Produce any side, as BC, indefinitely. Draw the diagonal EC and DH parallel to it. Draw EH. Now, consider the triangle CDE as cut off from the polygon and replaced by CHE. The magnitude of the polygon will not be changed, since CDE and CHE have the same base CE, and the same altitude, as their vertices lie in DH parallel to EC. From the polygon thus reduced we cut the triangle FHE, and replace it by its equivalent FHI, by drawing the diagonal FH, and the parallel EI. In like manner, by drawing FB and the parallel AC, we can replace FBA by its equivalent FCB. Hence, CFI is equivalent to ABCDEF. It is evident that a similar process would reduce a polygon of any number of sides to an equivalent triangle.

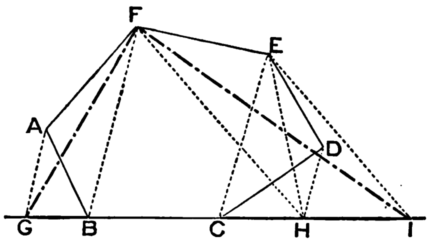

FIG. 226.

AREA.

PROPOSITION VI.

320. Theorem.—*The area of a rectangle is equal to the product of its base and altitude.*

DEM.—Let ABCD be a rectangle, then is its area equal to the base AB multiplied by the altitude AC.

If the sides AB and AC are commensurable, take some unit of length, as E, which is contained a whole number of times in each, as five times in AC, and eight times in AB, and apply it to the lines, dividing them respectively into five and eight equal parts. From the several points of division draw lines through the rectangle perpendicular to its sides. The rectangle will be divided into small parallelograms, which are all equal squares, as the angles are all right angles, and the sides all

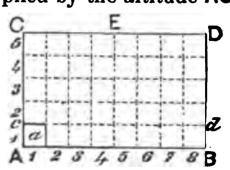

FIG. 227.

equal to each other. Each square is a unit of surface, and the area of the rectangle is expressed by the number of these squares, which is evidently equal to the number in the row on AB, multiplied by the number of such rows, or the number of linear units in AB multiplied by the number in AD.

If the two sides of the rectangle are not commensurable, take some very small unit of length which will divide one of the sides, as AC, and divide the rectangle into squares as before; the number of these squares will be the measure of the rectangle, except a small part along one side, not covered by the squares. By taking a still smaller unit, the part left unmeasured by the squares will be still less, and by diminishing the unit of length E, we can make the part unmeasured as small as we choose. It may, therefore, be made infinitely small by regarding the unit of measure as infinitesimal, and consequently is to be neglected.* Hence, in any case, the area of a rectangle is equal to the product of its base into its altitude. Q. E. D.

321. COR. 1.—*The area of a square is equal to the second power of one of its sides,* as in this case the base and altitude are equal.

322. COR. 2.—*The area of any parallelogram is equal to the product of its base into its altitude;* for any parallelogram is equivalent to a rectangle of the same base and altitude (***313***).

323. COR. 3.—*The area of a triangle is equal to one-half the product of its base and altitude;* for a triangle is one-half of a parallelogram of the same base and altitude (***314***).

324. COR. 4.—*Parallelograms or triangles† of equal bases are to each other as their altitudes; of equal altitudes, as their bases; and in general they are to each other as the products of their bases by their altitudes.*

PROPOSITION VII.

325. ***Theorem.***—*The area of a trapezoid is equal to the product of its altitude into one-half the sum of its parallel sides, or, what is the same thing, the product of its altitude and a line joining the middle points of its inclined sides.*

---

* This principle may be thus stated: An infinitesimal is a quantity conceived, *and to be treated,* as less than any assignable quantity; hence, as added to or subtracted from finite quantities, it has no value. Thus, suppose $\frac{m}{n} = a$, m, n, and a being finite quantities. Let c represent an infinitesimal; then $\frac{m \pm c}{n}$, or $\frac{m}{n \pm c}$, or $\frac{m \pm c}{n \pm c}$, is to be considered as still equal to a, for to consider it to differ from a by any amount we might name, would be to assign *some* value to c.

† By this is meant the *areas* of the figures.

DEM.—In the trapezoid ABCD draw either diagonal, as AC. It is thus divided into two triangles, whose areas are together equal to one-half the product of their common altitude (the altitude of the trapezoid), into their bases DC and AB, or this altitude into $\frac{1}{2}$(AB + DC).

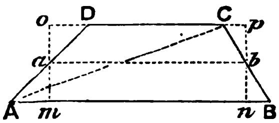

FIG. 228.

Secondly, if ab be drawn bisecting AD and CB, then is $ab = \frac{1}{2}$(AB + CD). For, through a and b draw the perpendiculars om and pn, meeting DC produced when necessary. Now, the triangles aoD and Aam are equal, since Aa = aD, angle $o = m$, both being right, and angle oaD = Aam being opposite. Whence Am = oD. In like manner we may show that Cp = nB. Hence, $ab = \frac{1}{2}(op + mn) = \frac{1}{2}$(AB + DC); and area ABCD, which equals *altitude* into $\frac{1}{2}$(AB + DC), = *altitude* into ab. Q. E. D.

PROPOSITION VIII.

326. Theorem.—*The area of a regular polygon is equal to one-half the product of its apothem into its perimeter.*

DEM.—Let ABCDEFG be a regular polygon whose apothem is Oa; then is its area equal to $\frac{1}{2}$ Oa (AB + BC + CD + DE + EF + FG + GA).

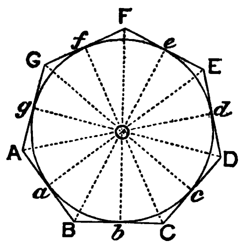

FIG. 229.

Drawing the inscribed circle, the radii Oa, Ob, etc., to the points of tangency, and the radii of the circumscribed circle OA, OB, etc. (**264, 265**), the polygon is divided into as many equal triangles as it has sides. Now, the apothem (or radius of the inscribed circle) is the common altitude of these triangles, and their bases make up the perimeter of the polygon. Hence, the area = $\frac{1}{2}$ Oa (AB + BC + CD + DE + EF + FG + GA). Q. E. D.

327. COR.—*The area of any polygon in which a circle can be inscribed is equal to one-half the product of the radius of the inscribed circle into the perimeter.*

The student should draw a figure and observe the fact. It is especially worthy of note in the case of a triangle. See *Fig.* 60.

PROPOSITION IX.

328. Theorem.—*The area of a circle is equal to one-half the product of its radius into its circumference.*

Dem.—Let Oa be the radius of a circle. Circumscribe any regular polygon. Now the area of this polygon is one-half the product of its apothem and perimeter. Conceive the number of sides of the polygon, indefinitely increased, the polygon still continuing to be circumscribed. The apothem continues to be the radius of the circle, and the perimeter approaches the circumference. When, therefore, the number of sides of the polygon becomes infinite, it is to be considered as coinciding with the circle, and its perimeter with the circumference. Hence the area of the circle is equal to one-half the product of its radius into its circumference. Q. E. D.

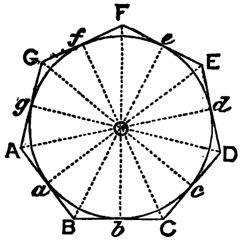

Fig. 230.

329. Def.—*A* ***Sector*** is a part of a circle included between two radii and their intercepted arc. *Similar Sectors* are sectors in different circles, which have equal angles at the centre.

330. Cor. 1.—*The area of a sector is equal to one-half the product of the radius into the arc of the sector.*

331. Cor. 2.—*The area of a sector is to the area of the circle as the arc of the sector is to the circumference, or as the angle of the sector is to four right angles.*

EXERCISES.

1. What is the area in acres of a triangle whose base is 75 rods and altitude 110 rods?

2. What is the area of a right angled triangle whose sides about the right angle are 126 feet and 72 feet?

3. If 3 lines be drawn from the vertex of a triangle to the base, dividing the base into parts which are to each other as 2, 3, and 5, how is the triangle divided? How does a line drawn from an angle to the middle of the opposite side divide a triangle?

4. Review the exercises on pages 49 and 50, giving the reasons, in each case.

SYNOPSIS.

- **EQUIVALENCY AND AREA.**
  - **EQUIVALENCY.**
    - Definition.
    - PROP. I. Of parallelograms.
      - *Cor.* Paral. and rectangle.
    - PROP. II. Of triangles.
      - *Cor.* 1. Triangle and rectangle.
      - *Cor.* 2. Of equal bases and equal altitudes.
    - PROP. III. Square on ½, ⅓, ¼ a line, etc.
    - PROP. IV. Trapezoid.
    - PROP. V. To reduce a polygon to a triangle.
  - **AREA.**
    - PROP. VI. Of rectangle.
      - *Cor.* 1. Of square.
      - *Cor.* 2. Any parallelogram.
      - *Cor.* 3. Of triangle.
      - *Cor.* 4. Relation of parallelograms and of triangles.
    - PROP. VII. Of trapezoid.
    - PROP. VIII. Of regular polygons.
      - *Cor.* Of any circumscribed polygon.
    - PROP. IX. Of a circle.
      - *Def.* Of sector.
      - *Cor.* 1. Area of sector.
      - *Cor.* 2. Relation of sector to circle.
  - EXERCISES.

SECTION X.

OF SIMILARITY.

332. The primary notion of similarity is *likeness of form*. Two figures are said to be similar which have the same shape, although they may differ in magnitude.* A more scientific definition is as follows:

333. ***Similar Figures*** are such as have their angles respectively equal, and their homologous sides proportional.

334. ***Homologous Sides*** of similar figures are those which are included between equal angles in the respective figures.

* The student should be careful, at the outset, to mark the fact that *similarity involves two things*, EQUALITY OF ANGLES and PROPORTIONALITY OF SIDES. It will appear that, in the case of triangles, if *one* of these facts exists, the other does also; but this is not so in other polygons, as is illustrated in PART I.

IN SIMILAR TRIANGLES, THE HOMOLOGOUS SIDES ARE THOSE OPPOSITE THE EQUAL ANGLES.

PROPOSITION I.

335. *Theorem.*—*Triangles which are mutually equiangular are similar.*

DEM.—Let ABC and DEF be two mutually equiangular triangles, in which A=D, B=E, and C=F; then are the sides opposite these equal angles proportional, and the triangles possess both requisites of similar figures; *i. e.*, they are mutually equiangular and have their homologous sides proportional, and are consequently similar.

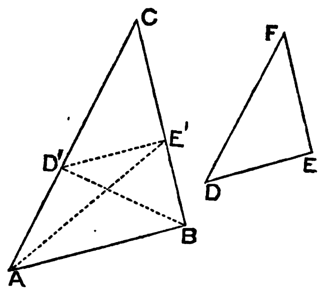

FIG. 231.

To prove that the sides opposite the equal angles are proportional, place the triangle DEF upon ABC, so that F shall coincide with its equal C, CE′=FE, and CD′=FD. Draw AE′, and D′B. Since angle CE′D′=CBA, D′E′ is parallel to AB, and the triangles D′E′A and D′E′B have a common base D′E′ and the same altitude, their vertices lying in a line parallel to their base, they are equivalent (*324*). Now, the triangles CD′E′ and D′E′A, having a common altitude, are to each other as their bases (*324*). Hence,

CD′E′ : D′E′A : : CD′ : D′A.

For like reason CD′E′ : D′E′B : : CE′ : E′B.

Then, since D′E′A and D′E′B are equivalent, the two proportions have a common ratio, and we may write CD′ : D′A : : CE′ : E′B.

By composition CD′ : CD′+D′A : : CE′ : CE′+E′B,
or CD′ : CA : : CE′ : CB, or FD : CA : : FE : CB.

In a similar manner, by applying angle E to B, we can show that FE : CB : : ED : BA. Therefore, FD : CA : : FE : CB : : ED : BA. Q. E. D.

336. COR. 1.—*If two triangles have two angles of the one respectively equal to two angles of the other, the third angles being equal* (***221***), *the triangles are similar.*

337. COR. 2.—*A line drawn through a triangle parallel to any side divides the other sides proportionally.*

Thus D′E′ being parallel to AB, it is shown in the proposition that CD′: D′A :: CE′ : E′B.

338. COR. 3.—*If any two lines cut a series of parallels, they are divided proportionally.*

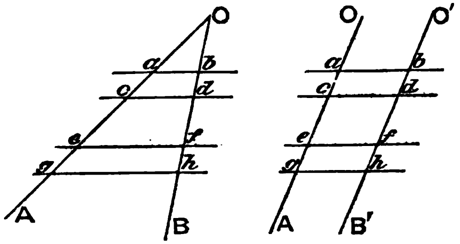

FIG. 232.

DEM.—If the two secant lines are parallel, as OA and O'B', the intercepted parts are equal, *i. e.*, $ac = bd$, $ce = df$, $eg = fh$, etc. (*242*). Hence, $ac : bd :: ce : df :: eg : fh$. Secondly, if the secant lines are not parallel, let them meet in some point, as O. Then, by the proposition, we have

$$Oa : ac :: Ob : bd \quad (1), \qquad \text{and also } Oc : ce :: Od : df \quad (2).$$

Taking the first by composition, it becomes

$$Oa + ac : ac :: Ob + bd : bd, \text{ or } Oc : ac :: Od : bd \quad (3).$$

Now, as the antecedents in (2) and (3) are the same, we have

$$ac : bd :: ce : df, \text{ or } ac : ce :: bd : df.$$

In like manner, we may show that

$$ce : df :: eg : fh, \text{ or } ce : eg :: df : fh.$$

PROPOSITION II.

339. ***Theorem.***—Conversely, *If two triangles have their corresponding sides proportional, they are similar.*

DEM.—In the triangles ABC and DFE, let FD : CA :: FE : CB :: DE : AB; then are the triangles similar.

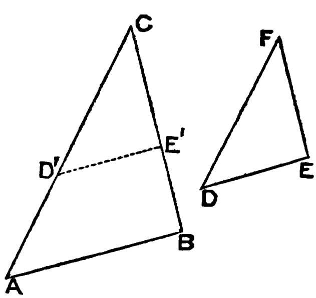

FIG. 233.

As one of the characteristics of similarity, viz., proportionality of sides, exists by hypothesis, we have only to prove the other, *i. e.*, that the triangles are mutually equiangular. Make CD' equal to FD, and draw D'E' parallel to AB. By the preceding proposition CD' (= FD) : CA :: D'E' : AB. But, by hypothesis, FD : CA :: DE : AB. Whence, D'E' = DE. In like manner CE' : CB :: CD' (= FD) : CA. But, by hypothesis, FE : CB :: FD : CA. Whence CE' = FE; and the triangle CD'E' is equal to the triangle FDE (*292*). Now, CD'E' and CAB are mutually equiangular, since D'E' is parallel to AB (*153*), and C is common. Hence,

the triangles ABC and DEF are mutually equiangular, and consequently similar. Q. E. D.

340. SCH.—As we now know that if two triangles are mutually equiangular, they are similar; or, if they have their sides proportional, they are similar, it will be sufficient hereafter, in any given case, to prove *either one* of these facts, in order to establish the similarity of two triangles. For, either fact being proved, the other follows as a consequence. See Section VI., PART I., for familiar illustrations of this most important subject.

PROPOSITION III.

341. Theorem.—*Two triangles which have the sides of the one respectively parallel or perpendicular to the sides of the other, are similar.*

DEM.—Let ABC and A′B′C′ be two triangles whose sides are respectively parallel or perpendicular to each other, then are the triangles similar.

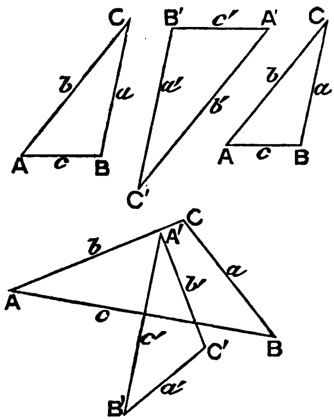

FIG. 234.

For, any angle in one triangle is either equal or supplementary to the angle in the other which is included between the sides which are parallel or perpendicular to its own sides. Thus A either equals A′, or A + A′ = 2 right angles (***281, 282, 283***). Now, if the corresponding angles are all supplementary, that is, if A + A′ = 2 R.A., B + B′ = 2 R.A., and C + C′ = 2 R.A., the sum of the angles of the two triangles is 6 right angles, which is impossible. Again, if one angle in one triangle equals the corresponding angle in the other, as A = A′, and the other angles are supplementary, the sum is 4 right angles plus twice the equal angle, which is impossible. Hence, two of the angles of one triangle must be equal respectively to two angles of the other; and, if two are equal, the third angle in one is equal to the third in the other (***221***). Hence, the triangles are mutually equiangular, and therefore similar (***335***). Q. E. D.

PROPOSITION IV.

342. Theorem.—*Two triangles, which have an angle in each equal, and the sides about the equal angles proportional, are similar.*

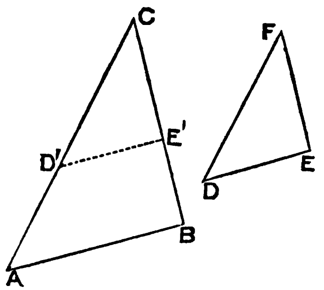

FIG. 235.

DEM.—In the triangles ABC and DEF let C = F, and AC : DF :: CB : FE; then are the triangles similar.

For, place F on its equal C, and let D fall at D'. Draw D'E' parallel to AB. Then AC : D'C (= DF) :: BC : CE' (337). But by hypothesis AC : DF :: BC : FE. ∴ CE' = FE, and the triangles D'CE' and DFE are equal (284). Therefore, D'CE' being equiangular with ACB, is similar to it (335); and as DFE is equal to D'CE', DFE is similar to ACB. Q. E. D.

PROPOSITION V.

343. Theorem.—*In any right angled triangle, if a line be drawn from the right angle perpendicular to the hypotenuse, it divides the triangle into two triangles, which are similar to the given triangle, and consequently similar to each other.*

DEM.—Let ACB be a triangle right-angled at C, and CD a perpendicular upon the hypotenuse AB; then are ACD and CDB similar to ACB, and consequently to each other.

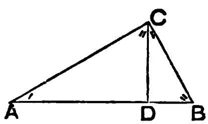

FIG. 236.

For, the triangles ACD and ACB have the angle A common, and a right angle in each; hence they are mutually equiangular, and consequently similar (*335*). For a like reason CDB and ACB are similar. Finally, as ACD and CDB are both similar to ACB, they are similar to each other. Q. E. D.

344. COR. 1.—*Either side about the right angle is a mean proportional between the whole hypotenuse and the adjacent segment.*

DEM.—This is a direct consequence of the similarity of the partial triangles with the whole triangle. Thus, comparing the homologous sides of ACD and ACB, we have AD : AC :: AC : AB;* and from CDB and ACB, we have DB : CB :: CB : AB.

345. COR. 2.—*The perpendicular is a mean proportional between the segments of the hypotenuse.*

DEM.—This is a consequence of the similarity of ACD and CDB. Thus, AD : CD : : CD : DB.

* Notice that AD of the triangle ACD is opposite angle ACD, and AC, its consequent, is of the triangle ACB, and opposite the angle B, which equals angle ACD. The student must sure that he knows in what order to take the sides, and *why*.

Queries.—To which triangle does the first CD belong? To which the second? Why is CD made the consequent of AD? Why, in the second ratio, are CD and DB to be compared?

346. Cor. 3.—*The square described on the hypotenuse of a right angled triangle is equivalent to the sum of the squares described on the other two sides.*

Dem.—From *Cor.* 1, $\overline{AC}^2 = AB \times AD$

and also $\overline{CB}^2 = AB \times DB.$

Therefore, adding, $\overline{AC}^2 + \overline{CB}^2 = AB\,(AD + DB) = \overline{AB}^2.$

347. Cor. 4.—*If a perpendicular be let fall from any point in a circumference upon a diameter, this perpendicular is a mean proportional between the segments of the diameter.*

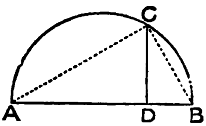

Fig. 287.

Dem.—Thus, AD : CD :: CD : DB, or $\overline{CD}^2 = AD \times DB$.

For, drawing AC and CB, ACB is a right angle, and the case falls under *Cor.* 2.

The chords AC and CB are mean proportionals between the whole diameter and their adjacent segments by *Cor.* 1.

348. Sch.—This proposition, with its corollaries, is perhaps the most fruitful in direct practical results of any in Geometry. *Cor.* 3 will be recognized as a demonstration of the Pythagorean proposition (***109***), Part I. There are many other demonstrations of exceeding beauty, some of which will be given in Part III. The one here given is the simplest, and shows best the way in which this truth grows out of the more general fact of similarity.

PROPOSITION VI.

349. Theorem.—*Regular polygons of the same number of sides are similar figures.*

Dem.—Let P and P′ be two regular polygons of the same number of sides,* a, b, c, d, etc., being the sides of the former, and a', b', c', d', etc., the sides of the latter. Now, by the definition of regular polygons, the sides a, b, c, d, etc., are equal each to each, and also a', b', c', d', etc. Hence, we have $a : a' :: b : b' :: c : c' :: d : d'$, etc. Again, the angles are equal, since n being the number of sides of each polygon, each angle is

$$\frac{n \times 2 \text{ right angles} - 4 \text{ right angles}}{n} \quad (\mathbf{256}).$$

Hence the polygons are mutually equiangular, and have their sides proportional; that is, they are similar. Q. E. D.

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* The student may construct two regular hexagons, if thought desirable.

350. COR. 1.—*The corresponding diagonals of regular polygons of the same number of sides are in the same ratio as the sides of the polygons.*

Let the student draw a figure and demonstrate the fact.

351. COR. 2.—*The radii of the inscribed, and also of the circumscribed circles, of regular polygons of the same number of sides, are in the same ratio as the sides of the polygons.*

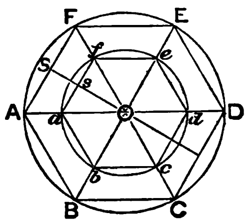

FIG. 238.

DEM.—Since the angles F and f are equal, and bisected by FO, the right angled triangles OSF, Osf are equiangular, and hence similar. Therefore FS : fs : : SO : sO or FO : fO. Whence, doubling both terms of the first couplet,

FA : fa : : SO : sO or FO : fO.

PROPOSITION VII.

352. Theorem.—*Circles are similar figures.*

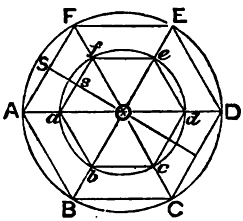

FIG. 239.

DEM.—Let Oa and OA be the radii of any two circles. Place the circles so that they shall be concentric, as in the figure. Inscribe the regular hexagons, as *abcdef*, ABCDEF. Conceive the arcs AB, BC, etc., of the outer circumference, bisected, and the regular dodecagon inscribed, and also the corresponding regular dodecagon in the inner circumference. These are similar figures by (***349***). Now, as the process of bisecting the arcs of the exterior circumference can be conceived as indefinitely repeated, and the corresponding *regular* polygons as inscribed in each circle, the circles may be considered as regular polygons of the same number of sides, and hence similar. Q. E. D.

353. COR.—Arcs of similar sectors are to each other as the radii of their circles; *i. e.*, arc fe : arc FE : : Of : OF.

SCH.—The circle is said to be the *Limit* of the inscribed polygon, and the circumference the *limit* of the perimeter. By this is meant that as the number of the sides of the inscribed polygon is increased it approaches nearer and nearer to equality with the circle. The apothem approaches equality with the radius, and hence has the radius for its limit. It is an axiom of great importance in mathematics that, *Whatever can be shown to be true of a magnitude as it approaches its limit indefinitely, is true of that limit.*

EXERCISES.

1. ***Prob.***—*To divide a given line into parts which shall be proportional to several given lines.*

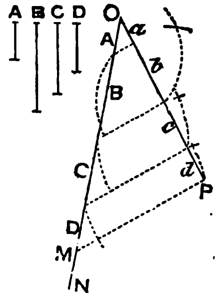

FIG. 240.

SOLUTION.—Let it be required to divide OP into parts proportional to the lines A, B, C, and D. Draw ON making any convenient angle with OP, and on it lay off A, B, C, and D, in succession, terminating at M. Join M with the extremity P, and draw parallels to MP through the other points of division. Then by reason of the parallels we shall have

A : B : C : D :: $a : b : c : d$, (*338*).

2. ***Prob.***—*To find a fourth proportional to three given lines.*

For the solution see (*89*). Repeat the process, and give the reasons.

3. ***Prob.***—*To find a third proportional to two given lines.*

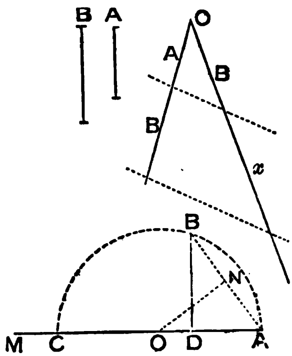

FIG. 241.

SOLUTION.—This may be solved as the two preceding. Thus, take any two lines, as A and B, for the given lines. We are to find a third line x, such that A : B :: B : x. The figure will suggest the details.

The following is a solution based on (*347*). Draw an indefinite line AM. Take AD = A, and erect BD = B. Join AB, and bisect it by the perpendicular ON. Then with O as a centre, and OA as a radius, describe a semi-circumference. This will pass through B. (Why?) Also AD : BD :: BD : CD (= x). (Why?)

4. Draw any straight line on the blackboard, and divide it into 5 equal parts, upon the principle used in the preceding solutions.

5. Review the exercises under (*89, 90*), and give the reasons.

6. ***Prob.***—*To find a mean proportional between two given lines.*

For the solution see (*110*). Repeat the process, and give the reasons for the method.

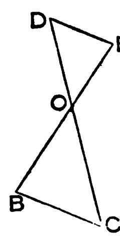

FIG. 242.

7. DE being parallel to BC, prove that the triangles DOE and BOC are similar, and hence that OD : OC :: OE : OB. Are the following proportions true?

OD : OC :: OE : OB, OD : DE :: OC : BC,
OD : OE :: OC : OB, OB : BC :: OE : DE.

8. Show that if ABCDEF is a regular polygon, A*bcdef* is also regular, *bc*, *cd*, etc., being parallel to BC, CD, etc. Show that any two similar polygons may be placed in similar relative positions, and hence show that the corresponding diagonals are in the same ratio as the homologous sides.

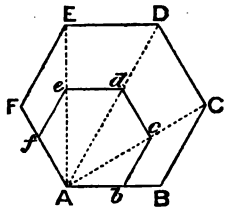

Fig. 243.

9. The sides of one triangle are 7, 9, and 11. The side of a second similar triangle, homologous with side 9, is $4\frac{1}{2}$. What are the other sides of the latter?

10. The diameter of a circle is 20. What is the perpendicular distance to the circumference from a point in the diameter 15 from one extremity? What are the distances from the point where this perpendicular meets the circumference to the extremities of the diameter?

SYNOPSIS.

Of Similarity.

- Primary notion of similarity.
- Definition of similarity.
- Homogeneity of sides. In general. In triangles.
- Conditions of Similarity in Triangles.
  - Prop. I. Mutually equiangular.
    - *Cor.* 1. Two angles equal.
    - *Cor.* 2. A parallel to a side.
    - *Cor.* 3. Lines cutting parallels.
  - Prop. II. Sides proportional.
    - *Sch.* Either of two facts sufficient.
  - Prop. III. Sides parallel or perpendicular.
  - Prop. IV. An angle equal in each, and sides proportional.
  - Prop. V. Perpendicular from right angle upon hypotenuse.
    - *Cor.* 1. Side about right angle.
    - *Cor.* 2. Perpendicular.
    - *Cor.* 3. Square on hypotenuse.
    - *Cor.* 4. Perpendicular on diameter.
    - *Sch.* Importance of this *Prop.* and *Cor's.*
- Prop. VI. Regular polygons similar.
  - *Cor.* 1. Corresponding diagonals.
  - *Cor.* 2. Radii of inscribed and circumscribed circles.
- Prop. VII. Circles similar.
  - *Sch.* Circle limit of polygon.
- Exercises.
  - *Prob.* To divide a line into proportional parts.
  - *Prob.* To find a fourth proportional.
  - *Prob.* To find a third proportional.
  - *Prob.* To find a mean proportional.

SECTION XI.

APPLICATIONS OF THE DOCTRINE OF SIMILARITY TO THE DEVELOPMENT OF GEOMETRICAL PROPERTIES OF FIGURES.

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354. The doctrine of similarity, as presented in the preceding section, is the chief reliance for the development of the geometrical properties of figures. This section will be devoted to the investigation of a few of the more elementary properties of plane figures, which we are able to discover by means of this doctrine.

OF THE RELATIONS OF THE SEGMENTS OF TWO LINES INTERSECTING EACH OTHER, AND INTERSECTED BY A CIRCUMFERENCE.

PROPOSITION I.

355. Theorem.—*If two chords intersect each other in a circle, their segments are reciprocally proportional; whence the product of the segments of one chord equals the product of the segments of the other.*

Dem.—Let the chords AC and BD intersect at O; then is AO : BO :: DO : CO, whence AO × CO = BO × DO.

For, draw AD and BC. The two triangles AOD and BOC are equiangular, and hence similar; since the angles at O are vertical, and consequently equal (*134*), and D = C, because both are measured by ½ arc AB (*210*). (A = B because both are measured by ½ arc DC; but it is only necessary to show that *two* angles are equal in order to show that the triangles are equiangular, and hence similar.) Now, comparing the homologous sides (those opposite the equal angles), we have AO : BO :: DO : CO; whence, AO × CO = BO × DO. Q. E. D.

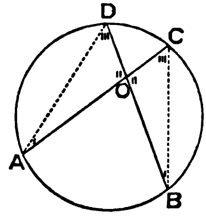

Fig. 244.

Queries.—Why is AO compared with BO? Why DO with CO? Would AO : CO :: BO : DO be true? Would AO : DO :: BO : CO? What is the force of the word "reciprocally," as used in the proposition?

PROPOSITION II.

356. Theorem.—*If from a point without a circle, two secants be drawn terminating in the concave arc, the whole secants are reciprocally proportional to their external segments; whence the product of one secant into its external segment equals the product of the other into its external segment.*

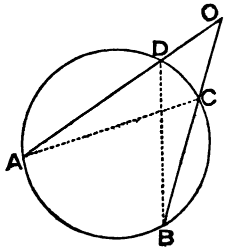

FIG. 245.

DEM.—OA and OB being secants, OA : OB :: OC : OD, and consequently OA × OD = OB × OC. For, drawing AC and DB, the two triangles ACO and BDO have angle O common, and A = B, since both are measured by ½ DC; hence the triangles are similar, and we have OA : OB :: OC : OD, and consequently OA × OD = OB × OC. Q. E. D.

Same queries as under the preceding demonstration.

PROPOSITION III.

357. Theorem.—*If from a point without a circle a tangent be drawn, and a secant terminating in the concave arc, the tangent is a mean proportional between the whole secant and its external segment; whence the square of the tangent equals the product of the secant into its external segment.*

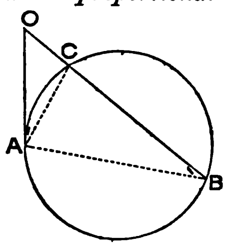

FIG. 246.

DEM.—OA being a tangent and OB a secant, OB : OA :: OA : OC, whence $\overline{OA}^2$ = OB × OC. For, drawing AB and AC, the triangles OAB and ACO have angle O common, and OAC = B, since each is measured by ½ arc AC; hence the triangles are similar, and OB : OA :: OA : OC, whence $\overline{OA}^2$ = OB × OC. Q. E. D.

OF THE BISECTOR OF AN ANGLE OF A TRIANGLE.

PROPOSITION IV.

358. Theorem.—*A line which bisects any angle of a triangle divides the opposite side into segments proportional to the adjacent sides.*

DEM.—Let CD bisect the angle ACB; then AD : DB :: AC : CB.

For, draw BE parallel to CD, and produce it till it meets AC produced, as at E. Now, by reason of the parallels CD and EB, angle ACD = AEB, and angle DCB = CBE (*152*). Whence, as ACD = DCB by hypothesis, E = CBE, and CE = CB (*227*). Also, since CD is parallel to EB, AD : DB :: AC : CE (*337*). Substituting for CE its equal CB, we have AD : DB :: AC : CB. Q. E. D.

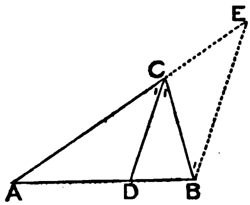

FIG. 247.

PROPOSITION V.

359. Theorem.—*If a line be drawn from any vertex of a triangle bisecting the exterior angle and intersecting the opposite side produced, the distances from the other vertices to this intersection are proportional to the adjacent sides.*

DEM.—Through the vertex C let CD be drawn, bisecting the exterior angle FCB, and intersecting AB produced in D; then AD : BD :: AC : CB.

For, draw BE parallel to AC. By reason of these parallels angle FCE (= BCE) = CEB (*152*), and consequently CB = BE. Also, by reason of the parallels, AD : BD :: AC : BE, or its equal CB (*335*). Q. E. D.

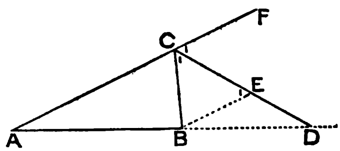

FIG. 248.

PROPOSITION VI.

360. Theorem.—*If a line be drawn bisecting any angle of a triangle and intersecting the opposite side, the rectangle of the sides about the bisected angle equals the rectangle of the segments of the third side, plus the square of the bisector.*

DEM.—Let CD bisect the angle ACB; then AC × CB = AD × DB + $\overline{CD}^2$.

For, circumscribe the circle about the triangle, produce the bisector till it meets the circumference at E, and draw EB. The triangles ADC and CBE are similar, since angle ACD = ECB, by hypothesis, and A = E, because each is measured by ½ arc CB. Therefore, AC : CE :: CD : CB, whence AC × CB = CE × CD = (DE + CD) CD = DE × CD + $\overline{CD}^2$. For DE × CD, substituting its equivalent AD × DB (*355*), we have AC × CB = AD × DB + $\overline{CD}^2$. Q. E. D.

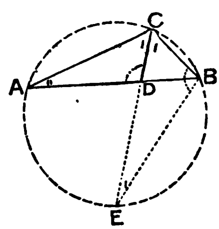

FIG. 249.

PROPOSITION VII.

361. Theorem.—*The bisectors of the angles of a triangle all pass through the same point, which is the centre of the inscribed circle.*

DEM.—Draw two lines bisecting two of the angles, and from their intersection draw a line to the other angle. Then show that the latter angle is bisected. By (Ex. 4, page 134) this point is shown to be the centre of the inscribed circle. [The student should fill out the demonstration.]

AREAS OF SIMILAR FIGURES.

PROPOSITION VIII.

362. Theorem.—*The areas of similar triangles are to each other as the squares described on their homologous sides.*

DEM.—Let ABC and DEF be any two similar triangles; then is

$$area\ ABC : area\ DEF :: \overline{CB}^2 : \overline{FE}^2 :: \overline{AC}^2 : \overline{DF}^2 : \overline{AB}^2 : \overline{DE}^2$$

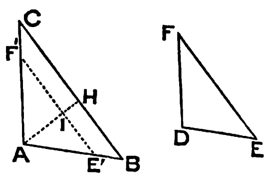

FIG. 250.

For, place the largest angle of the triangle DEF, as D, on its equal angle A, of the triangle ABC*; let E fall at E′, F at F′, and draw E′F′; then is triangle AE′F′ = DEF (*284*), and E′F′ is parallel to BC. Let fall a perpendicular from A to CB. Then AI is the altitude of AE′F′, and AH of ABC. Now, by similar triangles we have CB : F′E′ : : AH : AI.

But $\frac{1}{2}AH : \frac{1}{2}AI :: AH : AI$; and, multiplying corresponding terms, $\frac{1}{2}AH \times CB : \frac{1}{2}AI \times F'E' :: \overline{AH}^2 : \overline{AI}^2$. Whence, since

$\frac{1}{2}AH \times CB = area\ ABC$, and $\frac{1}{2}AI \times F'E' = area\ AE'F' = area\ DEF$, and

$AH : AI :: CB : FE :: AC : DF :: AB : DE$, or $\overline{AH}^2 : \overline{AI}^2 :: \overline{CB}^2 : \overline{FE}^2 :: \overline{AC}^2 : \overline{DF}^2 :: \overline{AB}^2 :: \overline{DE}^2$; we have

$$area\ ABC : area\ DEF :: \overline{CB}^2 : \overline{FE}^2 :: \overline{AC}^2 : \overline{DF}^2 :: \overline{AB}^2 : \overline{DE}^2. \quad \text{Q. E. D.}$$

PROPOSITION IX.

363. Theorem.—*The areas of similar polygons are to each other as the squares of the homologous sides of the polygons.*

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* The only object in taking the *largest* angle is to make the perpendicular fall *within* the triangle. Any two equal angles may be applied, and the demonstration is essentially the same.

DEM.—Let $abcdef$ and ABCDEF be two similar polygons. Designate the former by p, and the latter by P. Then $p : P :: \overline{ab}^2 :: \overline{AB}^2$ or as any other two homologous sides.

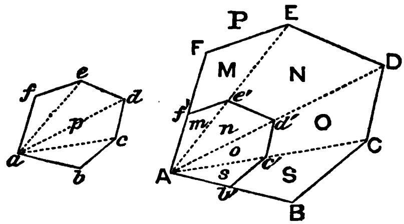


FIG. 251.

For, from the equal angles a and A drawing the diagonals, the corresponding partial angles into which a and A are divided are equal. [Let the student show why by ***342.***] Now take $Ab' = ab$, and draw $b'c'$, making angle $Ab'c' = b$. Then $b'c' = bc$, and $Ac' = ac$, since the triangles abc and $Ab'c'$ have two angles and the included side of one equal to two angles and the included side of the other. In like manner draw $c'd'$ making angle $b'c'd' = bcd$, $c'd' = cd$, and $Ad' = ad$. So, also, making angle $c'd'e' = cde$, and angle $d'e'f' = def$, $d'e' = de$, $e'f' = ef$, and $f'A = fa$. Hence the polygon $Ab'c'd'e'f' = p$, and its sides are respectively parallel to the corresponding sides of P. Now, let m, n, o, and s represent the triangles in which they stand, and M, N, O, and S the corresponding triangles of P, as AFE, etc. Triangles m and M being similar, and also n and N, we have,

$$m : M :: \overline{Ae'}^2 : \overline{AE}^2, \text{ and } n : N :: \overline{Ae'}^2 : \overline{AE}^2.$$

Whence $\quad m : M :: n : N.$

In like manner we can show that $n : N :: o : O$, and that $o : O :: s : S$.

Whence $m : M :: n : N :: o : O :: s : S$.

By composition, $(m+n+o+s)$ (or p) : $(M+N+O+S)$ (or P) $:: s : S$.

But $s : S :: \overline{Ab'}^2$ (or $\overline{ab}^2$) $: \overline{AB}^2$. Therefore $p : P :: \overline{ab}^2 : \overline{AB}^2$, or as the squares of any two homologous sides. Q. E. D.

364. COR. 1.—*Similar polygons* are to each other as the squares of their corresponding diagonals.*

In the demonstration we have $s : S :: \overline{Ac'}^2$ (or $\overline{ac}^2$) $: \overline{AC}^2$. Whence $p : P :: \overline{ac}^2 : \overline{AC}^2$. The same may be shown of any other corresponding diagonals.

365. COR. 2.—*Regular polygons* of the same number of sides are to each other as the squares of their homologous sides; since they are similar figures* (***349***).

366. COR. 3.—*Regular polygons* of the same number of sides are to each other as the squares of their apothems.*

For their apothems are to each other as their sides. Hence the squares of their apothems are to each other as the squares of their sides.

367. COR. 4.—*Circles are to each other as the squares of their radii* (***352***), *and as the squares of their diameters.*

* This is a common elliptical form for "The *areas* of, etc."

OF PERIMETERS AND THE RECTIFICATION OF THE CIRCUMFERENCE.

368. *The Rectification* of a curve is the process of finding its length.

The term *rectification* signifies making straight, and is applied as above, under the conception that the process consists in finding a straight line equal in length to the curve.

PROPOSITION X.

369. *Theorem.*—*The perimeters of similar polygons are to each other as their homologous sides, and as their corresponding diagonals.*

DEM.—Let a, b, c, d, etc., and A, B, C, D, etc., be the homologous sides of two similar polygons whose perimeters are p and P; then $p : P :: a : A :: b : B :: c : C$, etc.; and r and R being corresponding diagonals, $p : P :: r : R$. Since the polygons are similar, $a : A :: b : B :: c : C :: d : D$, etc. By composition, $(a+b+c+d+\text{etc.})$ (or p) : $(A+B+C+D+\text{ etc.})$ (or P) $:: a : A$, or as any other homologous sides. Also, as the homologous sides are to each other as the corresponding diagonals (*350*), $p : P :: r : R$. Q. E. D.

370. COR. 1.—*The perimeters of regular polygons of the same number of sides are to each other as the apothems of the polygons.*

For the apothems are to each other as the sides of the polygons (*351*).

371. COR. 2.—*The circumferences of circles are to each other as their radii, and as their diameters;* since they may be considered as regular polygons of the same number of sides (*352*).

PROPOSITION XI.

372. *Theorem.*—*The circumference of a circle whose radius is* 1, *is* 2π, *the numerical value of* π *being approximately* 3.1416.

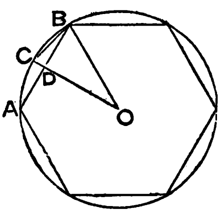


FIG. 252.

DEM.—We will approximate the circumference of a circle whose radius is 1, by obtaining, 1st, the perimeter of the regular inscribed hexagon; 2d, the perimeter of the regular inscribed dodecagon; 3d, the perimeter of the regular inscribed polygon of 24 sides; then of 48, etc.

In order to do this, let us find the relation between the chord of an arc and the chord of $\frac{1}{2}$ the arc in a circle whose radius is 1. Call the chord of an arc as

AB, C, and the chord of half the arc, as CB, c. Now, BDO is right angled at D, whence $\overline{BO}^2 = \overline{BD}^2 + \overline{DO}^2$ (*346*), or $DO = \sqrt{\overline{BO}^2 - \overline{BD}^2}$. But in the present case $BO = 1$; hence $DO = \sqrt{1 - \frac{1}{4}C^2}$. Taking DO from CO, we have $CD = 1 - \sqrt{1 - \frac{1}{4}C^2}$ From the right angled triangle BDC we have CB (or c) $= \sqrt{\overline{BD}^2 + \overline{CD}^2}$, or substituting $\frac{1}{2}C$ for BD, and $1 - \sqrt{1 - \frac{1}{4}C^2}$ for CD, this reduces to

$$c = \sqrt{2 - \sqrt{4 - C^2}}.$$

By the use of this formula, we make the following computations:

No. Sides.	Form of Computation.		Length of Side.	Perimeter.
6	See (*271*).		1.00000000	6.00000000
12	$c = \sqrt{2 - \sqrt{4 - 1^2}}$	=	.51763809	6.21165708
24	$c = \sqrt{2 - \sqrt{4 - (.51763809)^2}}$	=	.26105238	6.26525722
48	$c = \sqrt{2 - \sqrt{4 - (.26105238)^2}}$	=	.13080626	6.27870041
96	$c = \sqrt{2 - \sqrt{4 - (.13080626)^2}}$	=	.06543817	6.28206396
192	$c = \sqrt{2 - \sqrt{4 - (.06543817)^2}}$	=	.03272346	6.28290510
384	$c = \sqrt{2 - \sqrt{4 - (.03272346)^2}}$	=	.01636228	6.28311544
768	$c = \sqrt{2 - \sqrt{4 - (.01636228)^2}}$	=	.00818121	6.28316941

It now appears that the first four decimal figures do not change as the number of sides is increased; hence these figures will remain the same *how far soever we proceed.* We may therefore consider 6.28317, as *approximately* the circumference of a circle whose radius is 1, *i. e.*, $2\pi = 6.28317$, nearly; and $\pi = 3.1416$, nearly.

373. SCH.—The symbol π is much used in mathematics, and signifies, primarily, *the semi-circumference of a circle whose radius is* 1. $\frac{1}{2}\pi$ is therefore a symbol for a quadrant, 90°, or a right angle. $\frac{1}{4}\pi$ is equivalent to 45°, etc., the radius being always supposed 1, unless statement is made to the contrary. The numerical value of π has been sought in a great variety of ways, all of which agree in the conclusion that it cannot be exactly expressed in decimal numbers, but is approximately as given in the proposition. From the time of *Archimedes* (287 B.C.) to the present, much ingenious labor has been bestowed upon this problem. The most expeditious and elegant methods of approximation are furnished by the *Calculus*. The following is the value of π extended to fifteen places of decimals: 3.141592653589793.

PROPOSITION XII.

374. Theorem.—*The circumference of any circle is* $2\pi r$, r *being the radius.*

DEM.—The circumferences of circles being to each other as their radii, and

2π being the circumference of a circle whose radius is 1, we have $2\pi : circf. :: 1 : r$, whence $circf. = 2\pi r$.

375. Cor.—*The circumference of a circle is πD, D being the diameter*, since $2\pi r = \pi 2r = \pi D$.

AREA OF THE CIRCLE.

PROPOSITION XIII.

376. Theorem.—*The area of a circle whose radius is 1, is π.*

Dem.—The area of a circle is $\frac{1}{2} r \times$ *circumference* (***328***). When $r = 1$, *circumference* $= 2\pi$ (***372***); hence

area of circle whose radius is $1 = \frac{1}{2} \times 2\pi = \pi$. Q. E. D.

PROPOSITION XIV.

377. Theorem.—*The area of any circle is πr^2, r being the radius.*

Dem.—The areas of circles being to each other as the squares of their radii, and π being the area of a circle whose radius is 1, we have

$$\pi : \textit{area of any circle} :: 1^2 : r^2,$$

whence *area of any circle* $= \pi r^2$. Q. E. D.

378. Cor.—*The area of any sector is such a part of the area of the circle as the angle of the sector is of four right angles.*

379. Sch.—As the value of π cannot be exactly expressed in numbers, it follows that the area cannot. Finding the area of a circle has long been known as the problem of *Squaring the Circle*, *i. e.*, finding a square equal in area to a circle of given radius. Doubtless many hare-brained visionaries or ignoramuses will still continue the chase after the phantom, although it has long ago been demonstrated that the diameter of a circle and its circumference are incommensurable. It is, however, an easy matter to conceive a square of the same area as any given circle. Thus, let there be a rectangle whose base is equal to the circumference of the circle, and whose altitude is half the radius; its area is exactly equal to the area of the circle. Now, let there be a square whose side is a mean proportional between the altitude and base of this rectangle; the area of the square is exactly equal to the area of the circle.

EXERCISES.

1. Show that if a chord of a circle is conceived to revolve, varying in length as it revolves, so as to keep its extremities in the circumference while it constantly passes through a fixed point, the rectangle of its segments remains constant.

2. The two segments of a chord intersected by another chord are 6 and 4, and one segment of the other chord is 3. What is the other segment of the latter chord?

3. Show how PROP'S I., II., and III. may be considered as different cases of one and the same proposition.

SUG'S.—By stating Propositions I. and II. thus, *The distances from the intersection of the lines to their intersections with the circumference*, what follows? In *Fig.* 245, if the secant AO becomes a tangent, what does OD become?

4. In a triangle whose sides are 48, 36, and 50, where do the bisectors of the angles intersect the sides?

5. In the last example find the lengths of the bisectors.

6. Review the examples under (*111, 112, 113, 114*), and give the reasons.

7. In a circle whose radius is 20, what is the length of the arc of a sector whose angle is 30°? What is the area of this sector?

8. If a circle whose radius is 24 is divided into 5 equal parts by concentric circumferences, what are the diameters of the several circles? If the radius is r, and number of parts n?

9. ***Prob.***—*To divide a line in extreme and mean ratio; that is, so that the whole line shall be to the greater segment, as the greater segment is to the less.*

SOLUTION.—Let it be proposed to divide the line AB in extreme and mean ratio. At one extremity of the line, as B, erect a perpendicular equal to half the line, that is, make BO = ½ AB. With O as a centre, describe a circumference passing through B. Draw AO, and take AC equal to AD. Then is AB divided in extreme and mean ratio at C, so that AB : AC :: AC : CB. To prove it, produce AO to E. Now, AE : AB :: AB : AD (*357*), or by inversion, AB : AE :: AD : AB. By division, AB : AE — AB (= AE — DE) (or AD) (= AC) :: AD (= AC) : AB — AD (= AB — AC) (or CB). That is, AB : AC :: AC : CB.

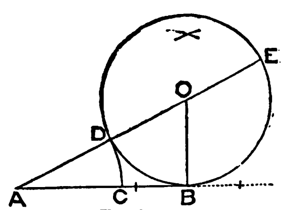
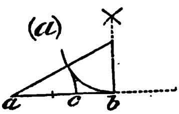


FIG. 253.

10. ***Prob.**—To inscribe a regular decagon in a circle, and hence a regular pentagon, and regular polygons of* 20, 40, 80, *etc., sides.*

SOLUTION.—Divide the radius in extreme and mean ratio, as at (a). Then is the greater segment ac the chord of a regular inscribed decagon, as ABCD, etc. To prove this, draw OA and OB, and taking OM $= ac =$ AB, a side of the polygon, draw BM. Now, OA : OM :: OM : MA by construction. As OM = AB, we have OA : AB :: AB : MA. Hence, considering the antecedents as belonging to the triangle OAB, and the consequents to the triangle BAM we observe that the two sides about the angle A, which is common to both triangles, are proportional, hence the triangles are similar (*342*). Therefore, ABM is isosceles, since OAB is, and angle BMA = A = OBA, and MB = BA = OM This makes OMB also isosceles, and the angle O = OBM. Again the exterior angle BMA = O + OBM = 2O; hence A, which equals BMA = 2O. Hence also OBA, which equals A, = 2O. Wherefore O is $\frac{1}{5}$ the sum of the angles of the triangle OAB, or $\frac{1}{5}$ of 2 right angles, $= \frac{1}{10}$ of 4 right angles. The arc AB is, therefore the measure of $\frac{1}{10}$ of 4 right angles, and is consequently $\frac{1}{10}$ of the circumference.



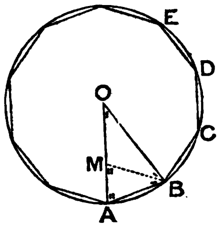


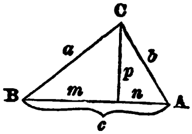
FIG. 254.

To construct the pentagon, join the alternate angles of the decagon. To construct the regular polygon of 20 sides, bisect the arcs subtended by the sides of the decagon, etc.

11. The projection of one line upon another in the same plane is the distance between the feet of two perpendiculars let fall from the extremities of the former upon the latter. Show that this projection is equal to the square root of the difference between the square of the line and the square of the difference of the perpendiculars.

12. In the triangle ABC, p being a perpendicular upon BA, prove that

$$m + n\ (= c) : a + b :: a - b : m - n.$$



State the fact as a proposition. Give the necessary modification when the perpendicular falls without the triangle.

SUG. $a^2 - m^2 = b^2 - n^2$, whence $a^2 - b^2 = m^2 - n^2$, etc.

13. The three sides of a triangle being 4, 5, and 6, find the segments of the last side, made by a perpendicular from the opposite angle. *Ans.* 3.75, and 2.25.

14. Same as above when the sides are 10, 4, and 7, and the perpendicular is let fall from the angle included by the sides 10 and 4. Draw the figure. Why is one of the segments nagative?

15. What is the area of a regular octagon inscribed in a circle whose radius is 1? What is its perimeter? What if the radius is 10?

SYNOPSIS.

Geometrical Properties developed by means of the Doctrine of Similarity.

- Importance of this doctrine.
- Relations of the Segments.
  - Prop. I. Of chords.
  - Prop. II. Of secants.
  - Prop. III. Of secants and tangents.
- Bisectors of the Angles of Triangles.
  - Prop. IV. How divide sides.
  - Prop. V. Of exterior angles.
  - Prop. VI. Length of in relation to other parts.
  - Prop. VII. All intersect at one point.
- Areas of Similar Figures.
  - Prop. VIII. Of triangles.
  - Prop. IX. Of polygons.
    - *Cor.* 1. As squares of diagonals.
    - *Cor.* 2. Regular polygons.
    - *Cor.* 3. As squares of apothems.
    - *Cor.* 4. Of circles.
- Perimeters and Rectification.
  - Definition of rectification.
  - Prop. X. Perimeters of similar polygons.
    - *Cor.* 1. Regular polygons.
    - *Cor.* 2. Circumferences as radii.
  - Prop. XI. Rectification of circumference whose radius is 1.
    - *Sch.* Signification and importance of π.
  - Prop. XII. Circumference of any circle $= 2\pi r$.
    - *Cor.* Also πD.
- Area of Circle.
  - Prop. XIII. Whose radius is 1.
  - Prop. XIV. Of any circle.
    - *Cor.* Of sector.
    - *Sch.* Squaring the circle.
- Exercises.
  - *Prob.* To divide a line in extreme and mean ratio.
  - *Prob.* To inscribe a regular decagon, etc.

CHAPTER II.

*SOLID GEOMETRY.**

SECTION I.

OF STRAIGHT LINES AND PLANES.

PERPENDICULAR AND OBLIQUE LINES.

380. ***Solid Geometry*** is that department of geometry in which the forms (or figures) treated are not limited to a single plane.

381. ***A Plane*** (or a *Plane Surface*) is a surface such that a straight line joining two points in it lies wholly in the surface.

Ill.—The surface of the blackboard is designed to be a plane. To ascertain whether it is truly so, take a ruler with a straight edge, and apply this edge in all directions upon it. If it always coincides, *i. e.*, touches throughout its whole length, the surface is a plane. Is the surface of the stove-pipe a plane? Will a straight line coincide with it in any direction? Will it in *every* direction?

PROPOSITION I.

382. ***Theorem.***—*Three points not in the same straight line determine the position of a plane.*

Dem.—Let A, B, and C be three points not in the same straight line; then one plane can be passed through them, and only one; *i. e.*, they determine the position of a plane.

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* In some respects, perhaps, "*Geometry of Space*" is preferable to this term; but, as neither is free from objections, and as this has the advantage of simplicity and long use, the author prefers to retain it.

For, pass a straight line through any two of these points, as A and B. Now, conceive any plane containing these two points; then will the line passing through them lie wholly in the plane (*381*). Conceive this plane to revolve on the line as an axis until the point C falls in the plane. Thus we have one plane passed through the three points. That there can be only one is evident, since when C falls in the plane, if it be revolved either way, C will not be in it. The same may be shown by first passing a plane through B and C, or A and C. There is, therefore, only one position of the plane in which it will contain the third point. Q. E. D.

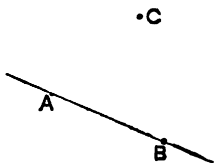

FIG. 255.

383. COR. 1.—*Through one line, or two points, an infinite number of planes can be passed.*

384. COR. 2.—*Two intersecting lines determine the position of a plane.*

DEM.—For, the point of intersection may be taken as one of the three points requisite to determine the position of a plane, and any other two points, one in each of the lines, as the other two requisite points. Now, the plane passing through these points contains the lines, for it contains two points in each line.

385. COR. 3.—*Two parallel lines determine the position of a plane.*

DEM.—For, pass a plane through one of the parallels, and conceive it revolved until it contains some point of the second parallel; then as the plane cannot be revolved either way from this position without leaving this point without it, it is the *only* plane containing the first parallel and this point in the second. But parallels lie in the same plane (*66*), whence the plane of the parallels must contain the first line, and the specified point in the second. Therefore, the plane containing the first line and a point in the second is the plane of the parallels, and is fixed in position.

386. COR. 4.—*The intersection of two planes is a straight line.*

For *two* planes cannot have even three points, *not in the same straight line*, common, much less an indefinite number, which would be required if we conceived the intersection (that is, the common points) to be any other than a straight line.

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387. ***A Perpendicular to a Plane*** is a line which is perpendicular to all lines of the plane passing through its foot. Conversely, the plane is perpendicular to the line.

PROPOSITION II.

388. ***Theorem.***—*A line which is perpendicular to two lines of a plane, at their intersection, is perpendicular to the plane.*

DEM.—Let PD be perpendicular to AB and CF at D; then is it perpendicular to MN, the plane of the lines AB and CF.

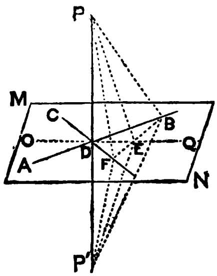

FIG. 226.

Let OQ be any other line of the plane MN, passing through D. Draw FB intersecting the three lines AB, CF, and OQ. Produce PD to P′, making P′D = PD, and draw PF, PE, PB, P′F, P′E, and P′B. Then is PF = P′F, and PB = P′B, since FD and BD are perpendicular to PP′, and PD = P′D (*284*). Hence, the triangles PFB and P′FB are equal (*292*); and, if PFB be revolved upon FB till P falls at P′, PE will fall in P′E. Therefore OQ has E equally distant from P and P′, and as D is also equidistant from the same points, OQ is perpendicular to PD at D (*130*). Now, as OQ is *any* line, PD is perpendicular to any line of the plane passing through its foot, and consequently perpendicular to the plane (*387*). Q. E. D.

389. COR.—*If one of two perpendiculars revolves about the other as an axis, its path is a plane perpendicular to the axis.*

Thus, if AB revolves about PP′as an axis, it describes the plane MN.

PROPOSITION III.

390. ***Theorem.***—*At any point in a plane one perpendicular can be erected to the plane, and only one.*

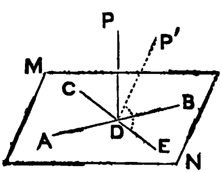

FIG. 227.

DEM.—Let it be required to show that one perpendicular, and only one, can be erected to the plane MN at D. Through D draw two lines of the plane, as AB and CE, at right angles to each other. CE being perpendicular to AB, let a line be conceived as starting from the position ED to revolve about AB as an axis. It will remain perpendicular to AB (*389*). Conceive it to have passed to P′D. Now, as it continues to revolve, P′DC diminishes continuously, and at the same rate as P′DE grows greater; hence, in one position of the revolving line, and in only one, as PD, PDE will equal PDC, and PD will be perpendicular to CE. Therefore, PD is perpendicular to two lines of the plane, at their intersection, and is the only line that can be thus perpendicular, whence it is perpendicular to the plane (*388*), and is the only perpendicular. Q. E. D.

PROPOSITION IV.

391. Theorem.—*If from any point in a perpendicular to a plane, oblique lines be drawn to the plane, those which pierce the plane at equal distances from the foot of the perpendicular are equal; and of those which pierce the plane at unequal distances from the foot of the perpendicular, those which pierce at the greater distances are the greater.*

DEM.—Let PD be a perpendicular to the plane MN, and PE, PE′, PE″, and PE‴, be oblique lines piercing the plane at equal distances ED, E′D, E″D, and E‴D, from the foot of the perpendicular; then $PE = PE' = PE'' = PE'''$. For each of the triangles PDE, PDE′, etc., has two sides and the included angle equal to the corresponding parts in the other.

Again, let FD be longer than E′D. Then is $PF > PE'$. For, take $ED = E'D$; then $PE = PE'$, by the preceding part of the demonstration. But $PF > PE$ by (*139*). Hence, $PF > PE'$. Q. E. D.

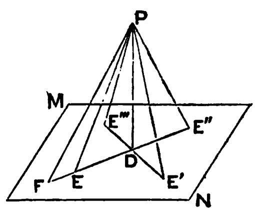

FIG. 258.

392. The Inclination of a line to a plane is measured by the angle which the line makes with a line of the plane passing through the point in which the line pierces the plane and the foot of a perpendicular to the plane from any point in the line.

Thus PFD is the inclination of PF to the plane MN.

393. COR. 1.—*The angles which oblique lines drawn from a common point in a perpendicular to a plane, and piercing the plane at equal distances from the foot of the perpendicular, make with the perpendicular, are equal; and the inclinations of such lines to the plane are equal.*

Thus the equality of the triangles, as shown in the demonstration, shows that $EPD = E'PD = E''PD = E'''PD$, and $PED = PE'D = PE''D = PE'''D$.

394. COR. 2.—Conversely, *If the angles which oblique lines drawn from a point in a perpendicular to a plane, make with the perpendicular, are equal, the lines are equal, and pierce the plane at equal distances from the foot of the perpendicular.*

DEM.—Thus, in the figure, let $DPE' = DPE''$; then $PE' = PE''$ and $DE' = DE''$. For, revolve DE′P about PD; DE′ will continue in the plane MN, and when angle DPE′ coincides with its equal DPE″, PE′ coincides with PE″, and DE′ with DE″.

395. Cor. 3.—Also, conversely, *Equal oblique lines from the same point in the perpendicular, pierce the plane at equal distances from the foot of the perpendicular.*

Dem.—Let PE′ = PE″; then is DE′ = DE″. For, let PDE′ revolve upon PD until E′D falls in E″D; then, if DE′ were less than DE″, PE′ would be less than PE″; and, if DE′ were greater than DE″, PE′ would be greater than PE″. But both of these conclusions are contrary to the hypothesis. Hence, as DE′ can neither be less nor greater than DE″, it must equal it. This corollary follows also from (*297*).

396. Cor. 4.—*The perpendicular is the shortest line that can be drawn to a plane from a point without, and measures the distance of the point from the plane.*

PROPOSITION V.

397. ***Theorem.***—*From a point without a plane one perpendicular can be drawn to the plane, and only one.*

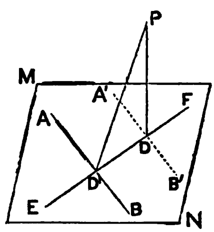

Fig. 259.

Dem.—Let it be required to show that one perpendicular can be drawn from P to the plane MN, and only one. Take AB, any line of the plane, and conceive PD′ perpendicular to it. Through D′ draw EF, a line of the plane, perpendicular to AB. Now, if PD′E = PD′F, they are both right angles, and PD′ is perpendicular to two lines of the plane passing through its foot, and hence perpendicular to the plane (*388*). If, however, PD′E does not equal PD′F, in the first instance, but PD′F < PD′E, conceive the line AB to move along the plane, continuing parallel to its primitive position, so as to cause D′ to move towards F, thus diminishing PD′E and increasing PD′F. At the same time observe that, if necessary in order to keep PD′A = PD′B*, EF can move along the plane parallel to its first position. Now, as PD′F increases, passing through all successive values, and PD′E diminishes in the same way, there will be some position of PD′, as PD, in which PDF = PDE, and as by hypothesis PDA′ remains = PDB′, PD becomes perpendicular to two lines passing through its foot, and hence perpendicular to the plane.

That there can be only one perpendicular is evident, since, if there were two, as PD′ and PD, there would be two right angles in the triangle PD′D.

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* According to the conception here used it would *not* be necessary.

398. COR.—*Through a given point in a line one plane can be passed perpendicular to the line, and only one.*

DEM.—Let D be the point in the line PD. Pass two lines through D, as EF, and A′B′, each perpendicular to PD; the plane of these lines is perpendicular to PD. Moreover, the plane must contain both these lines, for if it passed through D and did not contain DF, there would be one line of the plane, at least, which would pass through D and not be perpendicular to PD, which is impossible. Hence, there can be no other plane than the plane of the two perpendiculars EF and A′B′ which shall be perpendicular to PD, through D.

PROPOSITION VI.

399. Theorem.—*If from the foot of a perpendicular to a plane a line be drawn at right angles to any line of the plane, and this intersection be joined with any point in the perpendicular, the last line is perpendicular to the line of the plane.*

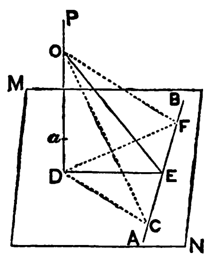

FIG. 260.

DEM.—From the foot of the perpendicular PD let DE be drawn perpendicular to AB, any line of the plane MN, and E joined with O, any point of the perpendicular; then is OE perpendicular to AB.

Take EF = EC, and draw CD, FD, CO, and FO. Now, CD = DF (?)*, whence CO = FO (?), and OE has O equally distant from F and C, and also E. Therefore, OE is perpendicular to AB (?). Q. E. D.

400. COR.—*The line* DE *measures the shortest distance between* PD *and* AB.

For, if from any other point in AB, as C, a line be drawn to D, it is longer than DE (?); and if drawn from C to *a*, any other point in PD than D, C*a* is longer than CD (?), and consequently longer than DE (?).

PARALLEL LINES AND PLANES.

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401. A Line is Parallel to a plane when the two will not meet, how far soever they be produced. The plane is also said to be parallel to the line.

* Hereafter the reason will be often left out, and the mark (?) will be used to indicate that the student is to supply it.

PROPOSITION VII.

402. Theorem.—*One of two parallel lines is parallel to every plane containing the other.*

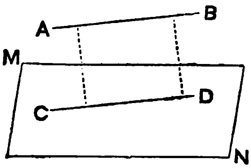

FIG. 261.

DEM.—AB being parallel to CD is parallel to any plane MN containing CD.

Since AB and CD are in the same plane (?), and as the intersection of their plane with MN is CD (?), if AB meets the plane MN, it must meet it in CD, or CD produced. But this is impossible (?). Whence AB is parallel to MN. Q. E. D.

403. COR. 1. *Through any given line a plane may be passed parallel to any other given line not in the plane of the first.*

For, through any point of the line through which the plane is to pass, conceive a line parallel to the second given line. The plane of the two intersecting lines is parallel to the second given line (?).

404. COR. 2.—*Through any point in space a plane may be passed parallel to any two lines in space.*

For, through the given point, conceive two lines parallel to the given lines; then is the plane of these intersecting lines parallel to the two given lines (?).

PROPOSITION VIII.

405. Theorem.—*If one of two parallels is perpendicular to a plane, the other is perpendicular also.*

DEM.—Let AB be parallel to CD, and perpendicular to the plane MN; then is CD perpendicular to MN.

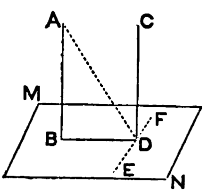

FIG 262.

For drawing BD in the plane MN, it is perpendicular to AB (?), and consequently to CD (?). Through D draw EF in the plane and perpendicular to BD, and join D with any point in AB, as A; then is EF perpendicular to AD (?). Now, EF being perpendicular to two lines, AD and BD of the plane ABDC, is perpendicular to the plane, and hence to any line of the plane passing through D, as CD. Therefore CD is perpendicular to BD and EF, and consequently to the plane MN (?). Q. E. D.

406. COR. 1.—*Two lines which are perpendicular to the same plane are parallel.*

Thus, AB and CD being perpendicular to the plane MN, if AB is not parallel to CD, draw a line through B which shall be. By the proposition this line is perpendicular to MN, and hence must coincide with AB (*398*).

407. COR. 2.—*Two lines parallel to a third not in their own plane are parallel to each other.*

DEM.—If AB and CD are parallel to EF, they are parallel to each other. Let MN be a plane passing through EF at F′, and to which EF is perpendicular; then are AB and CD respectively perpendicular to MN (?), and hence parallel (?). Q. E. D.

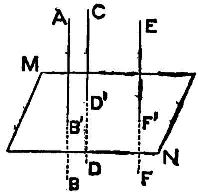

FIG. 263.

408. Parallel Planes are such as do not meet when indefinitely produced.

PROPOSITION IX.

409. Theorem.—*Two planes perpendicular to the same line are parallel to each other.*

DEM.—For, if they could meet in some point, as O, conceive two lines drawn from O, one in each plane, to the points where the perpendicular pierces the planes. We should then have two lines from the same point, perpendicular to the same line (?), which is impossible. Hence, as the planes cannot meet, they are parallel. Q. E. D.

PROPOSITION X.

410. Theorem.—*If a plane intersect two parallel planes, the lines of intersection are parallel.*

DEM.—Let AD intersect the parallel planes MN and PQ in AB and CD; then is AB parallel to CD. For, if AB and CD could meet, the planes MN and PQ would meet, as every point in AB is in MN, and every point in CD in PQ. Hence, AB and CD lie in the same plane, and do not meet how far soever they be produced; they are therefore parallel. Q. E. D.

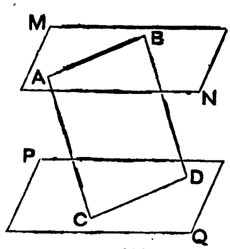

FIG. 264.

411. COR.—*Parallel lines intercepted between parallel planes are equal.*

Thus AC = BD if they are parallel. For, the intersections AB and CD, of the plane of these parallels, are parallel (?), and the figure ABDC is a parallelogram; whence AC = BD (?).

PROPOSITION XI.

412. Theorem.—*A line which is perpendicular to one of two parallel planes, is perpendicular to the other also.*

DEM.—Let AB be perpendicular to MN; then is it perpendicular to PQ, parallel to MN. For, pass two planes through AB, and let CA, DB, and EA, FB, be their intersections with the planes MN and PQ. Now CA and EA are perpendicular to AB (?); hence DB and FB being parallel to CA and EA (?) are perpendicular to AB (?). Therefore AB is perpendicular to two lines of the plane PQ, and consequently to the plane (?). Q. E. D.

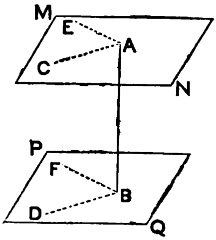

FIG. 265.

413. COR. 1.—*Through any point out of a plane, one plane can be passed parallel to the given plane, and only one.*

DEM.—To pass a plane through B parallel to MN, draw the perpendicular BA from B upon MN. Draw any two lines in the plane MN, through A, as CA and EA. Through B draw DB and FB parallel to CA and EA; then is PQ, the plane of these lines, perpendicular to AB, and hence parallel to MN. As the plane parallel to MN must contain FB and DB, and as but one plane can be passed through these lines, there can be only one plane through B parallel to MN.

414. ***The Distance*** *between two parallel planes at any point is measured by the perpendicular.*

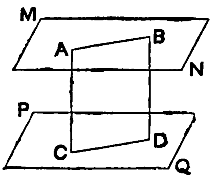

FIG. 266.

415. COR. 2.—*Parallel planes are everywhere equally distant from each other.*

DEM.—Let A and B be any two points in the plane MN, and AC and BD the perpendiculars from these points, let fall on the parallel plane PQ; then are they perpendicular to MN by the proposition, and since the figure ABCD is a parallelogram (?) [a rectangle, also (?)], AC = BD.

PROPOSITION XII.

416. ***Theorem.***—*Two angles lying in different planes, but having their sides parallel and extending in the same direction, are equal, and their planes are parallel.*

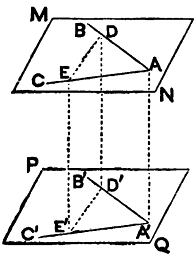

FIG. 267.

DEM.—Let A and A′ lie in the different planes MN and PQ, and have AB parallel to A′B′, and AC to A′C′; then A = A′, and MN and PQ are parallel.

For, take AD = A′D′, and AE = A′E′, and draw AA′, DD′, EE′, ED, and E′D′. Now, AD being equal and parallel to A′D′, AA′ = DD′ (?). For like reason AA′ = EE′, therefore EE′ = DD′. Again, since EE′ and DD′ are respectively parallel to AA′, they are parallel to each other (?), whence EDD′E′ is a parallelogram (?), and ED = E′D′. Hence the triangles ADE and A′D′E′ are

mutually equilateral, and A, opposite ED, is equal to A′, opposite E′D′ equal to ED.

Again, the plane of the angle BAC, MN, is parallel to PQ, the plane of B′A′C′. For, let a plane be passed through AC and revolved until it is parallel to PQ. It must cut DD′, which is parallel to AA′, and EE′, so that DD′ shall equal AA′ and EE′ (?); hence it must pass through D.

417. Cor. 1.—*If two intersecting planes be cut by parallel planes, the angles formed by the intersections are equal.*

Thus, AB′ and AE′ being cut by the parallel planes MN and PQ, AD is parallel to A′D′ (?), and lies in the same direction, and AE to A′E′. Hence BAC= B′A′C′ (?).

418. Cor. 2.—*If the corresponding extremities of three equal parallel lines not in the same plane, be joined, the triangles formed are equal, and their planes parallel.*

Thus, if AA′ = DD′ = EE′, the sides of the triangle AED are equal to the sides of A′E′D′, since the figures AD′, DE′, and EA′ are parallelograms (?), and the corollary comes under the proposition (?).

PROPOSITION XIII.

419. *Theorem.*—*The corresponding segments of lines cut by parallel planes are proportional.*

Dem.—Let AB, CD and EF be cut by the parallel planes MN, PQ, RS, and TU; then A*a* : C*e* :: *ab* : *ef* :: *b*B : *f*D, and A*a* : E*i* :: *ab* : *ik* :: *b*B : *k*F, and C*e* : E*i* :: *ef* : *ik* :: *f*D : *k*F.

For, join the extremities A and D, and E and D, and conceive the intersections of the plane of AB and AD with the parallel planes to be BD, *bd*, and *ac*. These lines are parallel (?), and A*a* : A*c* :: *ab* : *cd* :: *b*B : *d*D (?). For a similar reason, C*e* : A*c* :: *ef* : *cd* :: *f*D : *d*D (?). Whence, the consequents of the proportions being the same, the antecedents give A*a* : C*e* :: *ab* : *ef* :: *b*B : *f*D. In like manner we can show that C*e* : E*i* :: *ef* : *ik* :: *f*D : *k*F. [Let the student give the details.] From these proportions we have A*a* : E*i* :: *ab* : *ik* :: *b*B : *k*F (?). Q. E. D.

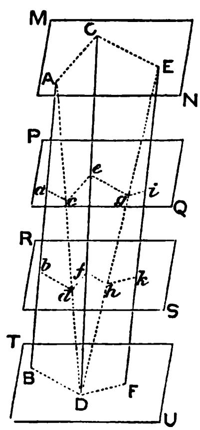

Fig. 268.

EXERCISES.

1. Designate any three points in the room, as one corner of the desk, a point on the stove, and some point in the ceiling, and show how you can conceive the plane of these points.

2. Show the position of two lines which will not meet, and yet are not parallel.

3. Conceive two lines, one line in the ceiling and one in the floor, which shall not be parallel to each other. What is the shortest distance between these lines?

4. The ceiling of my room is 10 feet above the floor. I have a 12 foot pole, by the aid of which I wish to determine a point in the floor directly under a certain point in the ceiling. How can I do it?

SUG.—Consult PROP. IV.

5. Upon what principle in this section is it that a stool with three legs always stands firm on a level floor, when one with four may not?

6. By the use of two carpenter's squares you can determine a perpendicular to a plane. How is it done?

7. If you wish to test the perpendicularity of a stud to a level floor, on how many sides of it is it necessary to measure the angle which it makes with the floor? By applying the right angle of the carpenter's square on *any* two sides of the stud, to test the angle which it makes with the floor, can you determine whether it is perpendicular or not?

8. We see in straight lines. If a line* be placed between our eye and a surface, it covers a certain space on the surface; this figure or space is said to be the *projection* of the line on that surface. Upon what principles in this section is it that the projections of straight lines are straight? Why is it that the projections of parallels which are parallel to the plane upon which we see them projected, are parallel, while parallel lines which are inclined to this plane are projected in oblique lines?

9. If a line is drawn at an inclination of 23° to a plane, what is the greatest angle which any line of the plane, drawn through the point where the inclined line pierces the plane, makes with the line? Can you conceive a line of the plane which makes an angle of 50° with the inclined line? Of 80°? Of 15°? Of 170°?

Hereafter, the student should make the synopses.

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* The term line is here used in its colloquial sense, and refers to a material representation, as a cord, the edge of a board, etc.

SECTION II.

OF SOLID ANGLES.

420. *A Solid Angle* is the opening between two or more planes, each of which intersects all the others. The lines of intersection are called *Edges*, and the planes, or the portion of the planes between the edges, where there are more than two, are called *Faces*.

421. *A Diedral Angle*, or simply a *Diedral*, is the opening between *two* intersecting planes.

422. *A Polyedral Angle*, called also simply a *Polyedral*, is the opening between *three* or more planes which intersect so as to have one common point, and only one. In the case of three intersecting planes the angle is called a *Triedral*. The point common to all the planes is called the *Vertex*. The plane angles enclosing a polyedral are the *Facial* angles.

423. *A Diedral (Angle) is measured* by the plane angle included by lines drawn in its faces from any point in the edge, and perpendicular thereto. A diedral angle is called right, acute, or obtuse, according as its measure is right, acute, or obtuse. Of course the magnitude of a solid angle is independent of the distances to which the edges may chance to be produced.

ILL'S.—The opening between the two planes **CABF** and **DABE** is a *Diedral* (angle), **AB** is the *Edge*, and **CABF** and **DABE** are the *Faces*. Let **MO** lie in the plane **AF**, perpendicular to the edge; and **NO** in **AE**, and also perpendicular to the edge; then the plane angle **MON** is the measure of the diedral. A diedral may be read by the letters on the edge, when there

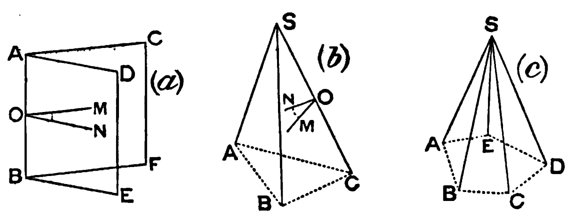

FIG. 269.

would be no ambiguity, or otherwise by these letters and one in each face; thus, the diedral in (*a*) may be designated as AB, or as C-AB-D.

In (*b*) we have a *Triedral* (angle). The *edges* are SA, SB, and SC; the *faces* ASB, BSC, and ASC: the *facial angles* are ASB, ASC, and BSC; and S is the *vertex*. Such an angle, and any polyedral (angle), may be read by naming the angle at the vertex, when there would be no ambiguity, or otherwise by naming the letter at the vertex, and then one in each edge; thus S-ABCDE designates the polyedral (*c*). The opening between the planes is the angle, in each case.

OF DIEDRALS.

424. A Diedral may be considered as generated by the revolution of a plane about a line of the plane, and hence we may see the propriety of measuring it by the angle included by two lines in its faces perpendicular to its edge, as stated in the preceding article.

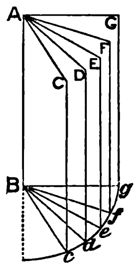

FIG. 270.

ILL.—Let AB be a line of the plane CB. Conceive *g*B perpendicular to AB. Now, let the plane revolve upon AB as an axis, whence *g*B describes a circle (?); and at any position of the revolving plane, as *f*BAF, since *f*B*g* measures the amount of revolution, it may be taken as the measure of the diedral *f*-BA-*g*. When *g*B has made $\frac{1}{4}$ of a revolution, the plane will have made $\frac{1}{4}$ of a revolution, and the diedral will be right.

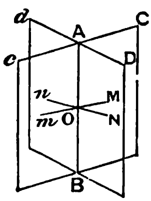

FIG. 271.

425. COR.—*Opposite diedrals are equal.*

Thus, if C-AB-D is measured by MON, *c*-AB-*d* is measured by the equal angle *n*O*m*.

PROPOSITION I.

426. ***Theorem.***—*Any line in one face of a right diedral, perpendicular to its edge, is perpendicular to the other face.*

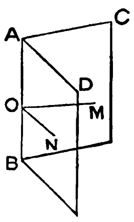

FIG. 272.

DEM.—In the face CB of the right diedral C-AB-D, let MO be perpendicular to the edge AB; then is it perpendicular to the face DB. For, draw ON in the face DB, and perpendicular to AB. Now, since the diedral is right, and MON measures its angle, MON is a right angle; whence MO is perpendicular to two lines of the plane DB, and consequently perpendicular to the plane. Q. E. D.

427. COR.—Conversely, *If one plane contain a line which is perpendicular to another plane, the diedral is right.*

Thus, if **MO** is perpendicular to the plane **DB**, **C-AB-D** is a right diedral. For **MO** is perpendicular to every line of **DB** passing through its foot (?); and hence is perpendicular to **ON**, drawn at right angles to **AB**. Whence **C-AB-D** is a right diedral, for it is measured by a right plane angle.

PROPOSITION II.

428. Theorem.—*If two planes are perpendicular to a third, their intersection is perpendicular to the third plane.*

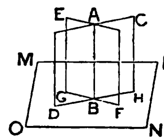

FIG. 273.

DEM.—If **CD** and **EF** are perpendicular to the plane **MN**, then is **AB** perpendicular to **MN**. For, **EF** being perpendicular to **MN**, **D-FG-E** is a right diedral, and a line in **EF** and perpendicular to **FG** at **B** is perpendicular to **MN**; also a line in the plane **CD**, and perpendicular to **DH** at **B**, is perpendicular to **MN** (?). Hence, as there can be one and only one perpendicular to **MN** at **B**, and as this perpendicular is in both planes, **CD** and **EF**, it is their intersection. Q. E. D.

PROPOSITION III.

429. Theorem.—*If from any point perpendiculars be drawn to the faces of a diedral angle, their included angle will be the supplement of the angle which measures the diedral.*

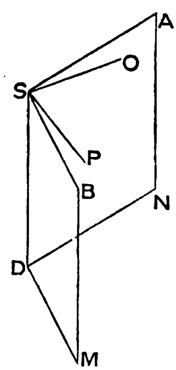

FIG. 274.

DEM.—Let **BD** and **AD** be any two planes including the diedral **A-SD-B**, then will two lines drawn from any point, perpendicular to these planes, include an angle which is the supplement of the measure of the diedral.

If the point from which the lines are drawn is not in the edge **SD**, we may conceive two lines drawn through any point, as **S**, in this edge, which shall be parallel to the two proposed, and hence include an equal angle, and have their plane parallel to the plane of the proposed angle (***416***). Let the latter lines be **SO** and **SP**. We are to show that **OSP** is supplemental to the measure of **A-SD-B**. A plane passed through **S**, perpendicular to the edge **SD**, will contain the lines **SO** and **SP** (***388***); and its intersections with the faces, as **SB** and **SA**, will form an angle (**ASB**) which is the measure of the diedral (***423***). Now, **PSA** = *a right angle* (?), and **OSB** = *a right angle* (?). Hence, **PSA** + **OSB** = 2 *right angles*. But **PSA** = **ASO** + **OSP**, and **OSB** = **BSP** + **OSP**. Adding these, and noticing that **BSP** + **OSP** + **ASO** = **ASB**, we have **PSA** + **OSB** = **ASB** + **OSP** = 2 *right angles; i. e.*, **OSP** is the supplement of **ASB**. Q. E. D.

OF TRIEDRALS.

430. Triedrals are *Rectangular*, *Birectangular*, or *Trirectangular*, according as they have one, two, or three, right diedral angles.

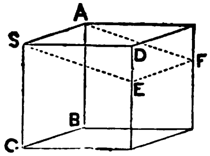

FIG. 275.

ILL'S.—The corner of a cube is a *Trirectangular* triedral, as S-ADC. Conceive the upper portion of the cube removed by the plane ASEF; then the angle at S, *i. e.*, S-AEC is a *Birectangular* triedral, A-SC-E and A-SE-C being right diedrals.

431. An Isosceles Triedral is one that has two of its facial angles equal. ***An Equilateral Triedral*** is one that has all three of its facial angles equal.

432. Two Symmetrical Triedrals are such as have the facial angles of the one equal to the facial angles of the other, each to each; but in which the equal facial angles are not similarly situated, and hence the triedrals are not necessarily capable of superposition.

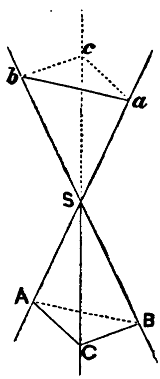

FIG. 276.

ILL'S.—Let the edges of the triedral S-ABC, be produced beyond the vertex, forming a second triedral S-*abc*; then are the two triedrals symmetrical, *i. e.*, the faces are equal plane angles, but disposed in a different order. Thus, ASB = *a*S*b*, ASC = *a*S*c*, and BSC = *b*S*c*; but the triedrals cannot be made to coincide. To show this fact, conceive the upper triedral detached, and the face *a*S*c* placed in its equal face ASC, S*a* in SA, and S*c* in SC. Now, the edge S*b*, instead of falling in SB will fall on the left of the plane ASC.

Symmetrical solids are of frequent occurrence: the two hands form an illustration; for, though the parts may be exactly alike, the hands cannot be placed so that their like parts will be similarly situated; in short, the left glove will not fit the right hand.

433. Two triedrals are ***Supplementary*** when the edges of one are perpendicular to the faces of the other.

PROPOSITION IV.

434. Theorem.—*The sum of any two facial angles of a triedral is greater than the third.*

DEM.—This proposition needs demonstration only in case of the sum of the two smaller facial angles as compared with the greatest (?). Let ASB and BSC each be less than ASC; then is ASB + BSC > ASC. For, make the angle ASb′ = ASB, and Sb′ = Sb, and pass a plane through b and b', cutting SA and SC in a and c. The two triangles aSb and aSb' are equal (?), whence $ab' = ab$. Now, $ab + bc > ac$ (?), and subtracting ab from the first member, and its equal ab' from the second, we have $bc > b'c$. Whence the two triangles bSc and b'Sc have two sides equal, but the third side bc > than the third side $b'c$, and consequently angle bSc > b'Sc. Adding ASB to the former, and its equal ASb′ to the latter, we have ASB + BSC > ASC. Q. E. D.

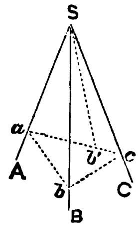

FIG. 277.

435. COR.—*The difference between any two facial angles of a triedral is less than the third facial angle* (?).

PROPOSITION V.

436. *Theorem.*—*The sum of the facial angles of a triedral may be anything between 0 and four right angles.*

DEM.—Let ASB, BSC, and ASC be the facial angles enclosing a triedral; then, as each must have some value, the sum is greater than 0, and we have only to show that ASB + ASC + BSC < 4 *right angles.* Produce either edge, as AS, to D. Now, in the triedral S-BCD, BSC < BSD + CSD. To each member of this inequality add ASB + ASC, and we have

ASB + ASC + BSC < ASB + ASC + BSD + CSD.

But, ASB + BSD = 2 right angles (?), and ASC + CSD = 2 *right angles;* whence ASB + ASC + BSD + CSD = 4 *right angles;* and consequently, ASB + ASC + BSC < 4 *right angles.* Q. E. D.

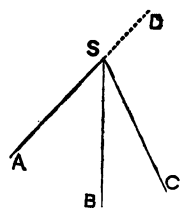

FIG. 278.

PROPOSITION VI.

437. *Theorem.*—*Two triedrals having the facial angles of the one equal to the facial angles of the other, each to each, and similarly arranged, are equal.*

DEM.—In the triedrals S and *s*, let ASB = *asb*, BSC = *bsc*, and CSA = *csa*; and let these facial angles occur in the same order, then is S-ABC = *s-abc*.

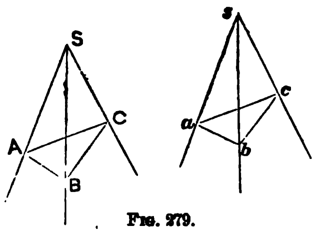

FIG. 279.

Take C, any point in SC, and make *sc*=SC, and draw AC and BC perpendicular to SC, and *ac* and *bc* perpendicular to *sc*; then ACB measures the diedral A-SC-B, and *acb* the diedral *a-sc-b*. Now the triangles SCB and *scb* are mutually equiangular (?) and have SC = *sc*; hence SB = *sb*, and CB = *cb*. For a like reason AC = *ac*, and SA = *sa*. Hence AB = *ab* (?), and the triangles ACB and *acb* are equal (?). Now, since angle ACB, measuring the diedral A-SC-B, equals angle *acb*, measuring the diedral *a-sc-b*, these diedrals are equal, and can be applied to each other. Applying these diedrals, since angle ASC = *asc*, and BSC = *bsc*, the edges AS and *as* coincide, as also do BS and *bs*, whence the triedrals coincide throughout, and are consequently equal. Q. E. D.

PROPOSITION VII.

438. *Theorem.*—*Of two supplementary triedrals, the facial angles of the one are the supplements of the diedrals* of the other.*

DEM.—Let S-ABC be any triedral; if a second triedral be formed with its edges perpendicular to the faces of S-ABC, one to each face respectively, then are the facial angles of the one, supplements of the diedrals of the other.

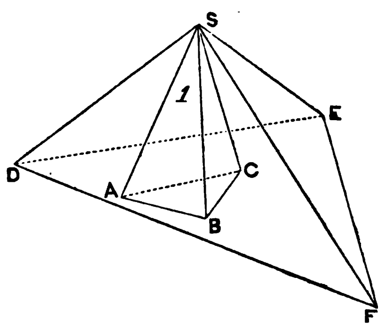

FIG. 280.

If the vertex of the second triedral is not at the vertex of the first, we may conceive a triedral formed by drawing three lines through the vertex S, as SE, SD, and SF, parallel to the edges of the given triedral; then will these edges be perpendicular to the same planes as the edges to which they are parallel (*405*), and hence the angle thus formed (S-EDF) will be a triedral supplemental to S-ABC (*433*), and the facial angles of the two having their edges parallel will be equal (*416*), and consequently the triedrals equal (*437*). Now, SE being perpendicular to ASB, and SF to ASC, angle ESF is supplemental to the diedral B-SA-C (*429*.) In

* Strictly speaking, of the *measures* of the diedrals.

like manner, SD being perpendicular to BSC, DSE is supplemental to A-SB-C, and DSF to A-SC-B.

Thus we have shown that the facial angles of S-EDF are the supplements of the diedrals of S-ABC. We are now to show that the facial angles of S-ABC are supplements of the diedrals of S-EDF; *i. e.*, that ASB is the supplement of D-SE-F, BSC of E-SD-F, and ASC of D-SF-E. Since SE is by hypothesis perpendicular to ASB, it is perpendicular to AS (***387***); and since SF is perpendicular to ASC, it is perpendicular to AS (***387***). Hence AS is perpendicular to the face FSE (?). In like manner we may show that SB is perpendicular to DSE, and SC to DSF; whence it follows from the preceding part of the demonstration, or directly from (***429***), that angle ASB is the supplement of D-SE-F, BSC of E-SD-F, and ASC of D-SF-E.

PROPOSITION VIII.

439. Theorem.—*The sum of the diedrals of a triedral may be anything between two and six right angles.*

DEM.—Each diedral being the supplement of a plane angle of the supplementary triedral, the sum of the three diedrals is 3 times 2 right angles, or 6 *right angles — the sum of the angles of the supplementary triedral.* But this latter sum may be anything between 0 and 4 right angles (?). Hence the sum of the diedrals may be anything between 2 and 6 right angles. Q. E. D.

PROPOSITION IX.

440. Theorem.—*An isosceles triedral and its symmetrical triedral are equal.*

DEM.—Let S-ABC be an isosceles triedral with the facial angle ASB = BSC; then is it equal to its symmetrical triedral S-*abc*.

For, revolve S-*abc* about S until S*b* falls in SB, and bring the plane S*ba* into the plane SBC; then, since the diedrals C-SB-A and *a*-S*b*-*c* are opposite, they are equal (***425***),* and the plane S*bc* will fall in SBA. Moreover, S*a* will fall in SC, since angle BSC = ASB (by hypothesis) = *b*S*a* (vertical to ASB). In like manner S*c* will fall in SA, and the triedrals will coincide, and are therefore equal. Q. E. D.

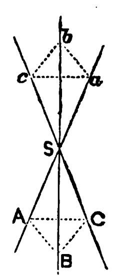

FIG. 281.

441. SCH.—If angle ASB is not equal to BSC, it is easy to see that the ap-

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* Should the pupil have difficulty in perceiving this, let him notice that CSB and *c*S*b* are parts of one and the same plane; and ASB and *a*S*b* are parts of another. Now *b*B is the intersection of these planes, and the diedrals mentioned are on opposite sides of this line of intersection.

plication will fail, notwithstanding the diedrals are equal, and the triedrals symmetrical.

442. Cor. 1.—*The diedrals opposite the equal facial angles of an isosceles triedral are equal.*

The diedral *b*-S*a*-*c* = B-SA-C being opposite, and *b*-S*a*-*c* = B-SC-A as shown in the demonstration; hence B-SA-C = B-SC-A.

443. Cor. 2.—Conversely, *If two diedrals of a triedral are equal, the triedral is isosceles.*

Dem.—If B-SA-C = B-SC-A, S-ABC is isosceles. For, revolving S-*abc* as before till the facial angle *a*S*c* falls in its equal (?) ASC, since the diedral B-SC-A = B-SA-C (by hypothesis) and the latter equals its opposite *b*-S*a*-*c*, the plane *b*S*a* will fall in the plane BSC; and, for like reasons, the plane *b*S*c* will fall in BSA. Now, as these planes coincide, their intersections S*b* and SB coincide, and the triedrals are equal; and the facial angle BSC = *b*S*a*. But *b*S*a* = ASB (?); hence ASB = BSC; *i. e.*, the triedral S-ABC is isosceles.

PROPOSITION X.

444. Theorem.—*Two symmetrical triedrals are equivalent.*

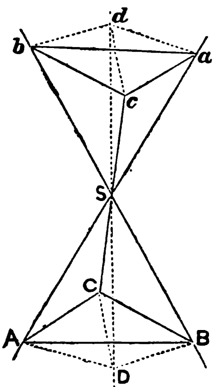

Fig. 282.

Dem.—S-ABC is equivalent to its symmetrical triedral S-*abc*.

For, let *d*D be so drawn that the angles DSA, DSC, and DSB shall be equal, and consequently *d*S*a* = *d*S*c* = *d*S*b*, and the latter respectively equal to the former. Then the isosceles symmetrical triedral S-DCB = S-*dcb*, S-DCA = S-*dca*, and S-ADB = S-*adb*. Whence the polyedral S-ABCD = S-*abcd*. Now, from the former subtracting S-ADB, and from the latter S-*adb*, there remains S-ABC = S-*abc*. Q. E. D.

445. Sch.—If *d*D fell within the given triedrals, they would be made up of the three equal isosceles triedrals, and hence equivalent.

PROPOSITION XI.

446. Theorem.—*Two triedrals which have two facial angles and the included diedral equal, each to each, are equal, or symmetrical and equivalent.*

Dem.—If the equal faces are on the same sides of the diedral in the two triedrals, the one figure can be applied to the other; and if they are on different

sides, the edges of one triedral may be produced, forming the symmetrical triedral, to which the other given triedral may be applied. [Let the student construct figures, and go through with the application.]

PROPOSITION XII.

447. Theorem.—*Two triedrals which have two diedrals and the included facial angle equal, are equal, or symmetrical and equivalent.*

DEM.—[Same as in the preceding. Let the student draw figures like those for the preceding, and go through with the details of the application.]

448. COR.—*It will be observed that in equal or in symmetrical triedrals, the equal facial angles are opposite the equal diedrals.*

PROPOSITION XIII.

449. Theorem.—*Two triedrals which have two facial angles of the one equal to two facial angles of the other, each to each, and the included diedrals unequal, have the third facial angles unequal, and the greater facial angle belongs to the triedral having the greater included diedral.*

DEM.—Let ASC $=$ *asc*, and ASB $=$ *asb*, while the diedral C-SA-B $>$ *c-sa-b*; then CSB $>$ *csb*.

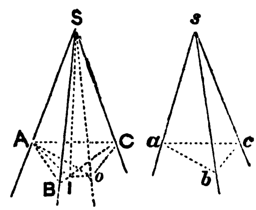

FIG. 283.

For, make the diedral C-SA-o $=$ *c-sa-b*: and taking ASo $=$ *asb*, bisect the diedral o-SA-B with the plane ISA. Draw oI and oC, and conceive the planes oSI and oSC. Now, the triedral S-AoC $=$ *s-abc*, since they have two facial angles and the included diedral equal (*446*). For a like reason S-AIo $=$ S-AIB, and the facial angle oSI $=$ ISB. Again, in the triedral S-IoC, oSI $+$ ISC $>$ oSC (*434*), and substituting ISB for oSI, we have ISB $+$ ISC (or BSC) $>$ oSC, or its equal *bsc*. Q. E. D.

450. COR.—Conversely, *If the two facial angles are equal, each to each, in the two triedrals, and the third facial angles unequal, the diedral opposite the greater facial angle is the greater.*

That is, if ASB $=$ *asb*, and ASC $=$ *asc*, while BSC $>$ *bsc*, the diedral B-AS-C $>$ *b-as-c*. For, if B-AS-C $=$ *b-as-c*, BSC $=$ *bsc* (*446*), and if B-AS-C $<$ *b-as-c*, BSC $<$ *bsc*, by the proposition. Therefore, as B-AS-C cannot be equal to nor less than *b-as-c*, it must be greater.

PROPOSITION XIV.

451. Theorem.—*Two triedrals which have the three facial angles of the one equal to the three facial angles of the other, each to each, are equal, or symmetrical and equivalent.*

DEM.—Let A, B, and C represent the facial angles of one, and a, b, and c the corresponding facial angles of the other. If $A = a$, $B = b$, and $C = c$, the triedrals are equal. For A being equal to a, and B to b, if, of their included diedrals, SM were greater than sm, C would be greater than c; and if diedral SM were less than diedral sm, C would be less than c, by the last corollary. Hence, as diedral SM can neither be greater nor less than diedral sm, it must be equal to it. For like reasons, diedral SN = diedral sn, and diedral SO = diedral so. Therefore, the triedrals are equal, or symmetrical, according to the arrangement of the faces. Thus, if SN and sn are both considered as lying on the same side of the planes MSO and mso, the triedrals are equal; but, if one lies on one side and the other on the opposite side of those planes (SN in front, and sn behind, for example), the diedrals are symmetrical, and hence equivalent.

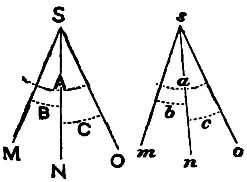

FIG. 284.

PROPOSITION XV.

452. Theorem.—*Two triedrals which have the three diedrals of the one equal to the three diedrals of the other, each to each, are equal, or symmetrical and equivalent.*

DEM.—In the two supplementary triedrals, the facial angles of the one will be equal to the facial angles of the other, each to each, since they are supplements of equal diedrals (*438*). Hence, the supplementary triedrals are equal or equivalent, by the last proposition. Now, the facial angles of the first triedrals are supplements of the diedrals of the supplementary; whence the corresponding facial angles, being the supplements of equal diedrals, are equal. Therefore, the proposed triedrals have their facial angles equal, each to each, and are consequently equal, or symmetrical and equivalent. Q. E. D.

453. COR.—*All trirectangular triedrals are equal.*

454. SCH.—The proof that two forms are equal, includes the fact that corresponding parts are equal.

OF POLYEDRALS.

455. ***A Convex Polyedral*** is a polyedral in which none of the faces, when produced, can enter the solid angle. A section of such a polyedral made by a plane cutting all its edges is a convex polygon. [See *Fig.* 285.]

PROPOSITION XVI.

456. ***Theorem.***—*The sum of the facial angles of any convex polyedral is less than four right angles.*

DEM.—Let S be the vertex of any convex polyedral. Let the edges of this polyedral be cut by any plane, as ABCDE, which section will be a convex polygon, since the polyedral is convex. From any point within this polygon, as O, draw lines to its vertices, as OA, OB, OC, etc. There will thus be formed two sets of triangles, one with their vertices at S, and the other with their vertices at O; and there will be an equal number in each set, for the sides of the polygon form the bases of both sets. Now, the sum of the angles of these two sets of triangles is equal. But the sum of the angles at the bases of the triangles having their vertices at S is greater than the sum of the angles at the bases of the triangles having their vertices at O, since SBA + SBC > ABC, SCB + SCD > BCD, etc. (*434*). Therefore the sum of the angles at S is less than the sum of the angles at O, *i. e.*, less than 4 right angles. Q. E. D.

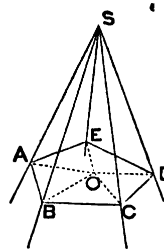

FIG. 285.

EXERCISES.

1. I have an iron block whose corners are all square (edges right diedrals, and the vertices trirectangular, or right, triedrals). If I bend a wire square around one of its edges, as *c*S′*d*, at what angle do I bend the wire? If I bend a wire obliquely around the edge, as *a*S*b*, at what angle can I bend it? If I bend it obliquely, as *e*S″*f*, at what angle can I bend it?

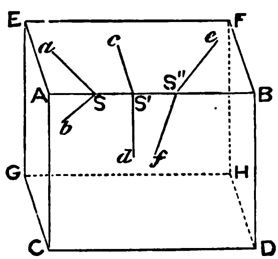

FIG. 286.

2. *Fig.* 286 represents the appearance of a rectangular parallelopiped, as seen from a certain position. Now, all the angles of such a solid are right angles: why is it that they nearly all *appear* oblique? Can you see a right parallelopiped from such a position that all the angles seen shall *appear* as right angles?

3. The diedral angles of crystals are measured with great care, in order to determine the substance of which the crystals consist. How must the measure be taken? If we measure obliquely around the edge, shall we get the true value of the angle?

4. Cut out any triedral from a block of wood (or a potato), and stick three pins into it, as near the vertex as you can, one in each face, and perpendicular to that face. What figure do the three pins form? What relation does the angle included between any two adjacent pins sustain to one of the diedrals of the block? Which ones are they that sustain this relation?

5. Can three planes intersect each other and yet not form a triedral angle? In how many ways? Can they all three have a common point, and yet not form a triedral?

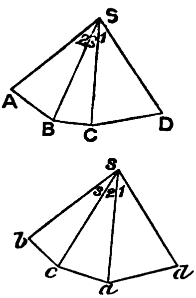

Fig. 287.

6. From a piece of pasteboard cut two figures of the same size, like ABCDS and *abcds*. Then drawing SB and SC so as to make 1 the largest angle and 3 the smallest, cut the pasteboard almost through in these lines, so that it will readily bend in them. Now fold the edges AS and DS together, and a triedral will be formed. From the piece *bcads* form a triedral in like manner, only let the lines *sc* and *sa* be drawn so as to make the angles 1, 2, and 3 of the same size as before, while they occur in the order given in *bcads*. Now, see if you can slip one triedral into the other, so that they will fit. What is the difficulty?

7. In the last case, if 1 equals $\frac{5}{6}$ of a right angle, $2 = \frac{1}{3}$ of a right angle, and $3 = \frac{2}{6}$ of a right angle, can you form the triedral? Why? If you keep increasing the size of 1, 2, and 3, until the sum becomes equal to 4 right angles, will it always be possible to form a triedral? How is it when the sum equals 4 right angles?

SECTION III.

OF PRISMS AND CYLINDERS.

457. *A Prism* is a solid, two of whose faces are equal, parallel polygons, while the other faces are parallelograms. The equal parallel polygons are the *Bases*, and the parallelograms make up the *Lateral* or *Convex Surface.* Prisms are triangular, quadrangular, pentagonal, etc., according to the number of sides of the polygon forming a base.

458. *A Right Prism* is a prism whose lateral edges are perpendicular to its bases. ***An Oblique*** prism is a prism whose lateral edges are oblique to its bases.

459. *A Regular Prism* is a right prism whose bases are regular polygons; whence its faces are equal rectangles.

460. *The Altitude* of a prism is the perpendicular distance between its bases: the altitude of a right prism is equal to any one of its lateral edges.

461. *A Truncated Prism* is a portion of a prism cut off by a plane not parallel to its base. A section of a prism made by a plane perpendicular to its lateral edges is called a *Right Section.*

ILL'S.—In the figure, (*a*) and (*b*) are both prisms: (*a*) is oblique and (*b*) right. PO represents the altitude of (*a*); and any edge of (*b*), as *b*B, is its altitude. ABCDEF, and *abcdef*, are lower and upper bases, respectively. Either portion of (*b*) cut off by an oblique plane, as *a'b'c'd'e'*, is a truncated prism.

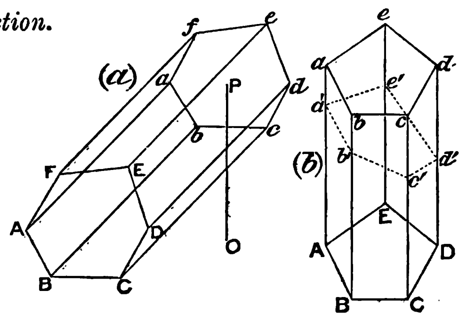

FIG. 288.

462. *A Parallelopiped* is a prism whose bases are parallelograms: its faces, inclusive of the bases, are consequently all parallel-

ograms. If its faces are all rectangular, it is a *rectangular* parallelopiped.

463. A Cube is a rectangular parallelopiped whose faces are all equal squares.

PROPOSITION I.

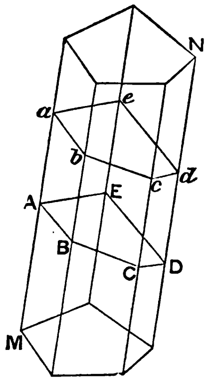

FIG. 289.

464. Theorem.—*Parallel plane sections of any prism are equal polygons.*

DEM.—Let ABCDE and *abcde* be parallel sections of the prism MN; then are they equal polygons.

For, the intersections with the lateral faces, as *ab* and AB, etc., are parallel, since they are intersections of parallel planes by a third plane (***410***). Moreover, these intersections are equal, that is, $ab =$ AB, $bc =$ BC, $cd =$ CD, etc., since they are parallels included between parallels (***242***). Again, the corresponding angles of these polygons are equal, that is, $a =$ A, $b =$ B, $c =$ C, etc., since their sides are parallel and lie in the same direction (***416***). Therefore the polygons ABCDE, and *abcde*, are mutually equilateral and equiangular; that is, they are equal. Q. E. D.

465. COR.—*Any plane section of a prism, parallel to its base, is equal to the base; and all right sections are equal.*

PROPOSITION II.

466. Theorem.—*If three faces including a triedral of one prism are equal respectively to three faces including a triedral of the other, and similarly placed, the prisms are equal.*

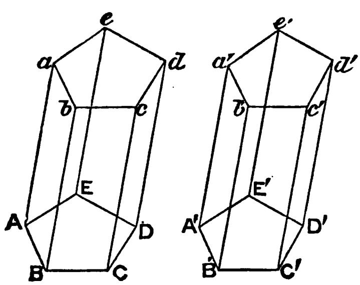

FIG. 290.

DEM.—In the prisms Ad, and A$'d'$, let ABCDE equal A'B'C'D'E', AB$ba =$ A'B'$b'a'$, and BC$cb =$ B'C'$c'b'$; then are the prisms equal.

For, since the facial angles of the triedrals B and B' are equal, the triedrals are equal (***451***), and being applied they will coincide. Now, conceiving A$'d'$ as applied to Ad, with B' in B, since the bases are equal polygons, they will coincide throughout; and the faces aB and a'B' will also coincide. Whence, as $a'b'$ falls in ab,

and $b'c'$ in bc, the upper bases, which are equal because equal to the equal lower bases, will coincide. Therefore the remaining edges will have two points common in each, and will consequently coincide.

467. Cor. 1.—*Two right prisms having equal bases and equal altitudes are equal.*

If the faces are not similarly arranged, one prism can be inverted.

468. Cor. 2.—*The above proposition and demonstration apply equally well to truncated prisms.*

PROPOSITION III.

469. Theorem.—*Any oblique prism is equivalent to a right prism, whose bases are right sections of the oblique prism, and whose edge is equal to the edge of the oblique prism.*

Dem.—Let LB be an oblique prism, of which *abcde* and *fghil* are right sections, and $gb =$ GB; then is *lb* equivalent to LB. For the truncated prisms *l*C and *e*B have the faces including any triedral, as C and B, equal and similarly placed (?), whence these prisms are equal (***466***). Now, from the whole figure, take away prism *l*C, and there remains the oblique prism LB; also, from the whole take away the prism *e*B, and there remains the right prism *lb*. Therefore, the right prism *lb* is equivalent to the oblique prism LB. Q. E. D.

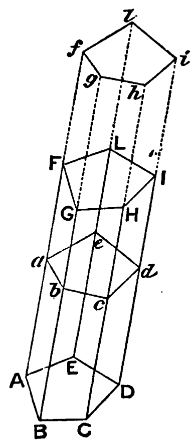

Fig. 291.

PROPOSITION IV.

470. Theorem.—*The opposite faces of a parallelopiped are equal and parallel.*

Dem.—Let A*c* be a parallelopiped, AC and *ac* being its equal bases (***462***); then are its opposite faces equal and parallel.

Since the bases are parallelograms, AB is equal and parallel to DC; and, since the faces are parallelograms, *a*A is equal and parallel to *d*D. Hence angle *a*AB = *d*DC, and their planes are parallel, since their sides are parallel and extend in the same directions. Therefore *a*B and *d*C are equal (***301***) and parallel parallelograms. In like manner it may be shown that *a*D is equal and parallel to *b*C.

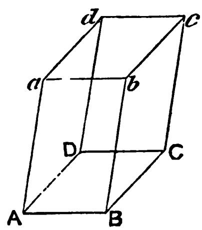

Fig. 292.

PROPOSITION V.

471. Theorem.—*The diagonals of a parallelopiped bisect each other.*

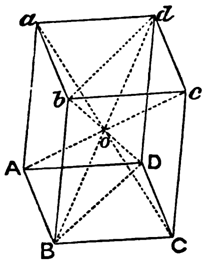

FIG. 293.

DEM.—Pass a plane through two opposite edges, as *b*B and *d*D. Since the bases are parallel, *bd* and BD will be parallel (**410**), and *b*BD*d* will be a parallelogram. Hence, *b*D and *d*B are bisected at *o* (?). For a like reason, passing a plane through *dc* and AB, we may show that *d*B and *c*A bisect each other, and hence that *c*A passes through the common centre of *d*B and *b*D. So also *a*C is bisected by *b*D, as appears from passing a plane through *ab* and DC. Hence, all the diagonals are bisected at *o*. Q. E. D.

472. COR.—*The diagonals of a rectangular parallelopiped are equal.*

PROPOSITION VI.

473. Theorem.—*A parallelopiped is divided into two equivalent triangular prisms by a plane passing through its diagonally opposite edges.*

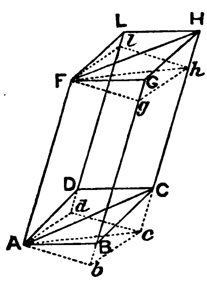

FIG. 294.

DEM.—Let H-ABCD be a parallelopiped, divided through its diagonally opposite edges FA and HC; then are the triangular prisms H-ABC, and L-ADC equivalent.

For this parallelopiped is equivalent to a right parallelopiped having a right section A*bcd* for its base, and AF for its edge (**469**), *i. e.*, H-ABCD is equivalent to *h*-A*bcd*. For the same reason the oblique triangular prism H-ABC is equivalent to the right triangular prism *h*-A*bc*; and L-ADC is equivalent to *l*-A*dc*. But *h*-A*bc* is equal to *h*-A*dc*, as they are right prisms with equal bases (**467**) and a common altitude. Hence, H-ABC is equivalent to L-ADC, as they are equivalent to two equal prisms. Q. E. D.

PROPOSITION VII.

474. Theorem.—*Any parallelopiped is equivalent to a rectangular parallelopiped having an equivalent base and the same altitude.*

DEM.—Let H-ABCD be any parallelopiped with all its faces oblique. 1st. By making the right section *ad*H*e*, and completing the parallelopiped *ad*H*ebc*C*f*, we have an equivalent right parallelopiped (**469**). 2d. Through the edge *ef* of this right parallelopiped make the right section *ea'b'f* and complete the parallelopiped *ea'b'f*H*d'c'*C, and we have a rectangular parallelopiped equivalent to the one previously formed (**469**), and hence equivalent to the given one. Now, the base of this rectangular parallelopiped, *i. e.*, *a'b'c'd'*, is equal to *abcd* (?), which in turn is equivalent to ABCD (?). Moreover, the altitude of the rectangular parallelopiped is the same as that of the given one, since their bases lie in the same parallel planes A*c'* and EC. Therefore, the parallelopiped H-ABCD is equivalent to the rectangular parallelopiped H-*a'b'c'd'*, which has an equivalent base and the same altitude. Q. E. D.

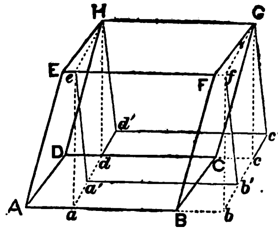

FIG. 295.

PROPOSITION VIII.

475. *Theorem.*—*The area of the lateral surface of a right prism is equal to the product of its altitude into the perimeter of its base.*

DEM.—The lateral faces are all rectangles, having for their common altitude the altitude of the prism (**460**). Whence the area of any face is the product of the altitude into the side of the base which forms its base; and the sum of the areas of the faces is the common altitude into the sum of the bases of the faces, that is, into the perimeter of the base of the prism. Q. E. D.

476. *A Cylindrical Surface* is a surface traced by a straight line moving so as to remain constantly parallel to its first position, while any point in it traces some curve. The moving line is called the *Generatrix*, and the curve traced by a point of the line is the *Directrix.*

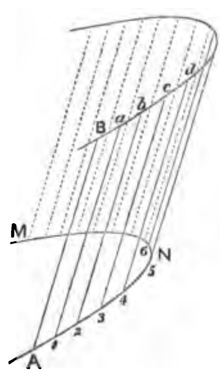

FIG. 296.

ILL.—Suppose a line to start from the position AB, and move towards N in

such a manner as to remain all the time parallel to its first position AB, while A traces the curve A 1 2 3 4 5 6 - - - - M. The surface thus traced is a *Cylindrical Surface;* AB is the *Generatrix*, and the curve ANM the *Directrix.*

477. A Circular Cylinder, called also a *Cylinder of Revolution,* is a solid generated by the revolution of a rectangle around one of its sides as an axis.

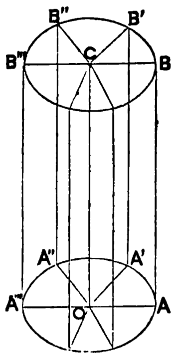

Fig. 297.

Ill.—Let COAB be a rectangle, and conceive it revolved about CO as an axis, taking successively the positions COA'B', COA''B'', etc.; the solid generated is a *Circular Cylinder*, or a cylinder of revolution. The revolving side AB is the generatrix of the surface, and the circumference OA (or CB) is the directrix. This is the only cylinder treated in Elementary Geometry, and is usually meant when the word *Cylinder* is used without specifying the kind of cylinder.

478. The Axis of the cylinder is the fixed side of the rectangle. The side of the rectangle opposite the axis generates the *Convex Surface;* while the other sides of the rectangle, as OA and CB, generate the *Bases*, which in the cylinder of revolution are circles. Any line of the surface corresponding to some position of the generatrix is called an *Element* of the surface.

479. A Right Cylinder is one whose elements are perpendicular to its base. In such a cylinder any element is equal to the axis. *A Cylinder of Revolution* (**477**) is *right.*

480. A prism is said to be inscribed in a cylinder, when the bases of the prism are inscribed in the bases of the cylinder, and the edges of the prism coincide with elements of the cylinder.

PROPOSITION IX.

481. Theorem.—*The area of the convex surface of a cylinder of revolution is equal to the product of its axis into the circumference of its base,* i. e., $2\pi RH$, H *being the axis and* R *the radius of the base.*

DEM.—Let a right prism, with any regular polygon for its base, be inscribed in the cylinder, as *k-abcdef*, in the cylinder whose axis is HO. The area of the lateral surface of the prism is HO (= *hb*) into the perimeter of its base, *i. e.*, HO × ($ab + bc + cd + de + ef + fa$). Now, bisect the arcs *ab*, *bc*, etc., and inscribe a regular polygon of twice the number of sides of the preceding, and on this polygon as a base construct the right inscribed prism with double the number of faces that the first had. The area of the lateral surface of this prism is HO × *the perimeter of its base.* In like manner conceive the operation of inscribing right prisms with regular polygonal bases continually repeated; it will *always* be true that the area of the lateral surface is equal to HO × *the perimeter of the base.* But the circumference of the base of the cylinder is the limit toward which the perimeters of the inscribed polygons forming the bases of the prisms constantly approach, and the convex surface of the cylinder is the limit of the lateral surface of the inscribed prism. Therefore, the area of the convex surface of the cylinder is HO into the circumference of the base. Finally, if R is the radius of the base, $2\pi R$ is its circumference. This multiplied by H the altitude, *i. e.*, $H \times 2\pi R$, or $2\pi RH$, is the area of the convex surface of the cylinder.

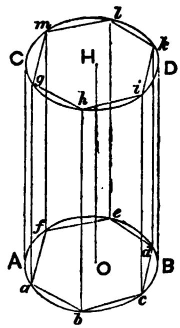

FIG. 298.

PROPOSITION X.

482. Theorem.—*The volume of a rectangular parallelopiped is equal to the product of the three edges of one of its triedrals.*

DEM.—Let H-CBFE be a rectangular parallelopiped. 1st. Suppose the edges commensurable, and let BC be 5 units in length, BA 4, and BF 7 Now conceive a cube, as *d-fb*B*g*, whose edge is one of these linear units. This cube may be used as the unit of volume. Conceive the parallelopiped O-*ca*B*b*, whose length is 7, and whose edges *ca* and *cb* are 1 (the linear unit of measure assumed). This parallelopiped will contain as many of the units of volume as there are linear units in BF: we suppose 7. Again, conceive the parallelopiped whose base is ECBF and altitude PE, one of the linear units. This parallelopiped will contain as many of the former as there are linear units in BC: we suppose 5. Hence this last volume is $5 \times 7 = 35$. Finally, there will

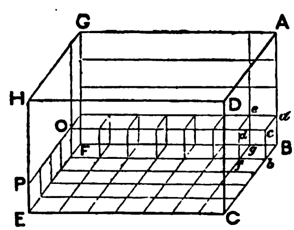

FIG. 299.

be as many times this number of units of volume in the whole parallelopiped as AB contains linear units, or $4 \times 35 = 140$. Hence, when the edges are commensurable, the volume is the product of the three edges including a triedral.

2nd. When the edges are not commensurable, we reach the same conclusion by taking successively a smaller and smaller linear unit. Thus, for a first approximation take some aliquot part of one edge, as $\frac{1}{10}$ of FB. Now, by hypothesis this is not contained an exact number of times in BC, nor in BA. But conceive it as applied to BC as many times as it can be; the remainder will be less than $\frac{1}{10}$ FB. In like manner conceive it applied to AB. The volume of the parallelopiped included by these edges will be measured by the product of the edges. Now conceive the linear unit smaller. The unmeasured portion will be less. Thus, by supposing the linear unit to diminish indefinitely, we see that *it will always remain true* that the measure is the product of the three edges forming a triedral.

483. Cor. 1.—*The volume of a cube is the third power of its edge.*

484. Sch.—This fact gives rise to the term *cube*, as used in arithmetic and algebra, for "third power."

485. Cor. 2.—*The volume of a rectangular parallelopiped is equal to the product of its altitude into the area of its base, the linear unit being the same for the measure of all the edges.*

486. Cor. 3.—*The volume of any parallelopiped is equal to the product of its altitude and the area of its base.*

For any parallelopiped is equivalent to a rectangular parallelopiped having an equivalent base and the same altitude (***474***).

487. Cor. 4.—*Parallelopipeds of the same or equivalent bases are to each other as their altitudes, and those of the same altitudes are to each other as their bases. And, in general, parallelopipeds are to each other as the products of their bases and altitudes.*

PROPOSITION XI.

488. Theorem.—*The volume of any prism is equal to the product of its altitude into its base.*

DEM.—1st. Let E-ABD be a triangular prism. Complete the parallelopiped E-ABCD. Then is E-ABD = $\frac{1}{2}$ E-ABCD (*473*). But the volume of E-ABCD is equal to its altitude into its base; hence the volume of E-ABD is equal to its altitude into $\frac{1}{2}$ ABCD, or ABD.

2d. Any prism may be divided into partial, triangular prisms, by passing planes through one edge and all the other non-adjacent edges, as in the figure. Let H be the altitude of the whole prism, then is it also the common altitude of the partial prisms. Now, the volume of each triangular prism is H into its base; hence, the sum of the volumes is H into the sum of the bases, *i.e.*, H into the base of the whole prism.

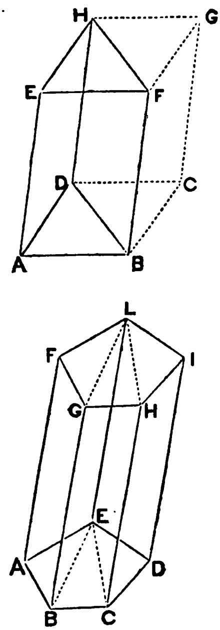

FIG. 300.

489. COR. 1.—*The volume of a right prism is equal to the product of its edge into its base.*

490. COR. 2.—*Prisms of the same altitude are to each other as their bases; and prisms of the same or equivalent bases are to each other as their altitudes; and, in general, prisms are to each other as the products of their bases and altitudes.*

PROPOSITION XII.

491. Theorem.—*The volume of a cylinder of revolution is equal to the product of its base and altitude,* i. e., πR^2H, H *being the altitude and* R *the radius of the base.*

DEM.—Inscribe any regular right prism in the cylinder, as in (*481*). The volume of this prism is equal to the product of its base and altitude; and this continues to be the fact as the number of sides of the polygon forming the base is successively doubled, and the prism approaches equality with the cylinder. Hence, as the volume of the prism is *always* equal to the product of its base and altitude, and as the altitude of the prism remains equal to the altitude of the cylinder, this fact is true when the number of the sides of the base of the prism is *infinitely* multiplied; whence the volume of the cylinder is equal to the product of its base and altitude. Now, R being the radius of the base, the area of the base is πR^2 (?): hence, the volume of the cylinder is equal to πR^2H.

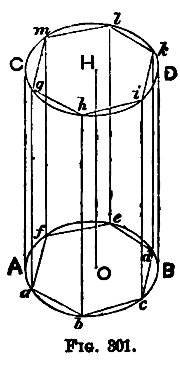

FIG. 301.

492. COR.—*The volume of any cylinder is equal to the product of its base into its altitude.*

This can be demonstrated in a manner altogether analogous to the case given in the proposition.

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493. ***Similar Solids*** are such as have their corresponding solid angles equal and their homologous edges proportional.

494. ***Similar Cylinders*** of revolution are such as have their altitudes in the same ratio as the radii of their bases.

495. ***Homologous Edges*** of similar solids are such as are included between equal plane angles in corresponding faces.

ILL'S.—The idea of similarity in the case of solids is the same as in the case of plane figures, viz., that of *likeness of form*. Thus, one would not think such a cylinder as *one* joint of stovepipe, similar to another composed of a hundred joints of the same pipe. One would be *long* and *very slim* in proportion to its length, while the other would not be thought of as *slim*. But, if we have two cylinders the radii of whose bases are 2 and 4, and whose lengths are respectively 6 and 12, we readily recognize them as of the same shape: they are similar.

PROPOSITION XIII.

496. ***Theorem.***—*The lateral surfaces of similar right prisms are to each other as the squares of their edges (or altitudes) and as the squares of any two homologous sides of their bases,* i. e., *as the squares of any two homologous lines.*

DEM.—Let A, B, C, D, and E, be the sides of the base of one right prism whose edge (equal to its altitude) is H, and a, b, c, d, and e, the homologous sides of a similar prism whose edge is h. Letting $A + B + C + D + E = P$, and $a + b + c + d + e = p$, we have

$P : p :: A : a :: B : b :: C : c$, etc. (?).

But by hypothesis, $H : h :: A : a :: B : b$, etc.

Hence, $P : p :: H : h$ (?).

Now, $H : h :: H : h$ (?).

Whence, $P \times H : p \times h :: H^2 : h^2$ (?).

And as $H^2 : h^2 :: A^2 : a^2 :: B^2 : b^2$, etc.,

we have $P \times H : p \times h :: A^2 : a^2 :: B^2 : b^2$, etc.

But P × H is the area of the lateral surface of one prism and $p \times h$ of the other, whence the truth of the theorem appears.

PROPOSITION XIV.

497. Theorem.—*The volumes of similar prisms are to each other as the cubes of their homologous edges, and as the cubes of their altitudes.*

DEM.—Let H-ABCDE and h-$abcde$ be two similar prisms, of which A and a are corresponding triedrals. Placing a so that it will coincide with A, all the faces and edges of one will be parallel to or coincident with the corresponding parts of the other, by definition (*493*). Let fall the perpendicular FP upon the common base, or its plane produced, so that FP shall equal the altitude of H-ABCDE, and OP, intercepted between the planes of the upper and lower bases of h-$abcde$, shall be its altitude. Call the former altitude H, and the latter h. Since FP and AF are cut by parallel planes, we have

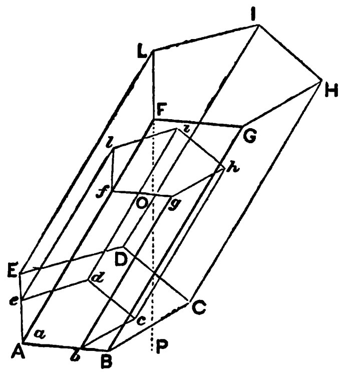

FIG. 302.

AF : af :: H : h; and AB : ab :: H : h, since by definition AF : af :: AB : ab, etc. Call the base of H-ABCDE B, and of h-$abcde$ b. Now, as the bases are similar polygons,

$$B : b :: \overline{AB}^2 : \overline{ab}^2 :: H^2 : h^2.$$

But $$H : h :: AB : ab :: H : h.$$

Hence, $$B \times H : b \times h :: \overline{AB}^3 : \overline{ab}^3 :: H^3 : h^3.$$

Now, as B × H and $b \times h$ are the volumes of the respective prisms, and as $\overline{AB}^3 : \overline{ab}^3$ as the cubes of any other homologous edges are to each other, the truth of the theorem is demonstrated.

PROPOSITION XV.

498. Theorem.—*The convex surfaces of similar cylinders of revolution are to each other as the squares of their altitudes, and as the squares of the radii of their bases.*

DEM.—Let H and h be the altitudes, and R and r the radii of the bases of two similar cylinders; the convex surfaces are $2\pi RH$ and $2\pi rh$ (*481*). Now,

$$2\pi RH : 2\pi rh :: RH : rh \ (?) \ (1).$$

By hypothesis, $H : h :: R : r$, or $\frac{H}{R} = \frac{h}{r}$ and $\frac{R}{H} = \frac{r}{h}$.

Multiplying the terms of the second couplet of (1) by these equals, we have,

$$2\pi RH : 2\pi rh :: H^2 : h^2,$$

and $$2\pi RH : 2\pi rh :: R^2 : r^2. \quad \text{Q. E. D.}$$

PROPOSITION XVI.

499. Theorem.—*The volumes of similar cylinders of revolution are to each other as the cubes of their altitudes, or as the cubes of the radii of their bases.*

DEM.—Using the same notation as in the last demonstration, the student should be able to give the reasons for the following steps.

$R : r :: H : h$ (?), whence $\pi R^2 : \pi r^2 :: H^2 : h^2$ (?). Multiplying the last proportion by $H : h :: H : h$, we have $\pi R^2 H : \pi r^2 h :: H^3 : h^3$, or as $R^3 : r^3$, since $H^3 : h^3 :: R^3 : r^3$ (?). Now, $\pi R^2 H$ and $\pi r^2 h$ are the volumes of the cylinders (?); hence the volumes are to each other as the cubes of the altitudes, or as the cubes of the radii of the bases. Q. E. D.

SCH.—It is a general truth, that the surfaces of similar solids, *of any form*, are to each other as the squares of homologous lines; and their volumes are as the cubes of such lines.

EXERCISES.

1. A farmer has two grain bins which are parallelopipeds. The front of one bin is a rectangle 6 feet long by 4 high, and the front of the other a rectangle 8 feet long by 4 high. They are built between parallel walls 5 feet apart. The bottom and ends of the first, he says, are "square" (he means, it is a rectangular parallelopiped), while the bottom and ends of the other slope, *i. e.*, are oblique to the front. What are the relative capacities of the bins?

2. How many square feet of boards in the walls and bottom of the first bin mentioned in *Ex.* 1?

3. An average sized honey bee's cell is a right hexagonal prism, .8 of an inch long, with faces $\frac{3}{20}$ of an inch wide. The width of the face is always the same, but the length of the cell varies according to the space the bee has to fill. Are honey bee's cells similar? Is a honey bee's cell of the dimensions given above, similar to a wasp's cell which is 1.6 inches long, and whose face is .3 of an inch wide? How much more honey will the wasp's cell hold than the honey bee's?

4. How many square inches of sheet-iron does it take to make a joint of 7-inch stovepipe 2 feet 4 inches long, allowing an inch and a half for making the seam?

5. A certain water-pipe is 3 inches in diameter. How much water is discharged through it in 24 hours, if the current flows 3 feet per

minute? How much through a pipe of twice as great diameter, at the same rate of flow?

6. What is the ratio of the length of a hogshead holding 125 gallons, to the length of a keg of the same shape, holding 2 gallons?

7. What are the relative amounts of cloth required to clothe 3 men of the same form (similar solids), one being 5 feet high, another 5 feet 9 inches, and the other 6 feet, provided they dress in the same style? If the second of these men weighs 156 lbs., what do the others weigh?

8. If a man $5\frac{1}{2}$ feet high weighs 160 lbs., and a man 3 inches taller weighs 180 lbs., which is the stouter in proportion to his height?

9. I have a prismatic piece of timber from which I cut two blocks both 5 feet long measured along one edge of the stick; but one block is made by cutting the stick square across (a right section), and the other by cutting both ends of it obliquely, making an angle of 45° with the same face of the timber. Which block is the greater? Which has the greater lateral surface?

10. How many cubic feet in a log 12 feet long and 2 feet 5 inches in diameter? How many square feet of inch boards can be cut from such a log, allowing $\frac{1}{4}$ for waste in slabs and sawing?

SECTION IV.

OF PYRAMIDS AND CONES.

500. A Pyramid is a solid having a polygon for its base, and triangles for its lateral faces. If the base is also a triangle, it is called a triangular pyramid, or a tetraedron (*i. e.*, a solid with four faces). The vertex of the polyedral angle formed by the faces is the *vertex* of the pyramid.

501. The Altitude of a pyramid is the perpendicular distance from its vertex to the plane of its base.

502. A Right Pyramid is one whose base is a regular

polygon, and the perpendicular from whose vertex falls at the middle of the base. This perpendicular is called the *axis*.

503. A Frustum of a pyramid is a portion of the pyramid intercepted between the base and a plane parallel to the base. If the cutting plane is not parallel to the base, the portion intercepted is called a *Truncated* pyramid.

504. The Slant Height of a right pyramid is the altitude of one of the triangles which form its faces. The *Slant Height of a Frustum* of a right pyramid is the portion of the slant height of the pyramid intercepted between the bases of the frustum.

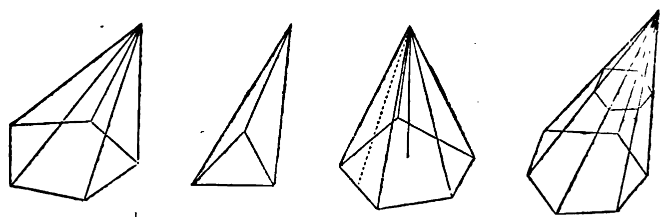

Fig. 303.

Ill's.—The student will be able to find illustrations of the definitions in the accompanying figures.

505. A Conical Surface is a surface traced by a line which passes through a fixed point, while any other point traces a curve. The line is the *Generatrix,* and the curve the *Directrix.* The fixed point is the *Vertex.* Any line of the surface corresponding to some position of the generatrix is called an *Element* of the surface.

506. A Cone of Revolution is a solid generated by the revolution of a right angled triangle around one of its sides, called the *Axis.* The hypotenuse describes the *Convex Surface* of the cone, and corresponds to the generatrix in the preceding definition. The other side of the triangle describes the *Base.* This cone is *right,* since the perpendicular (the axis) falls at the middle of the base. The *Slant Height* is the distance from the vertex to the circumference of the base, and is the same as the hypotenuse of the generating triangle.

507. The terms *Frustum* and *Truncated* are applied to the cone in the same manner as to the pyramid.

508. A pyramid is said to be *Inscribed* in a cone when the base of the pyramid is inscribed in the base of the cone, and the edges of the pyramid are elements of the surface of the cone. The two solids have a common vertex and a common altitude.

509. If the generatrix be considered as an indefinite straight line passing through a fixed point, the portions of the line on opposite sides of the point will each describe a conical surface. These two surfaces, which in *general* discussions are considered but one, are called ***Nappes.*** The two nappes of the same cone are evidently alike.

ILL'S.—In the figure, (*a*) represents a conical surface which has the curve ACB for its directrix, and SA for its generatrix. The figures indicate the successive positions of the point A, as it passes around the curve, while the point S remains fixed. (*b*) represents a *Cone of Revolution*, or a right cone with a circular base. It may be considered as generated in the general way, or by the right angled triangle SOA revolving about SO as an axis. SA describes the convex surface, and OA the base. The figure (*c*) represents the *Frustum* of a cone, the portion above the plane *abc* being supposed removed. Figure (*d*) represents the two nappes of an oblique cone.

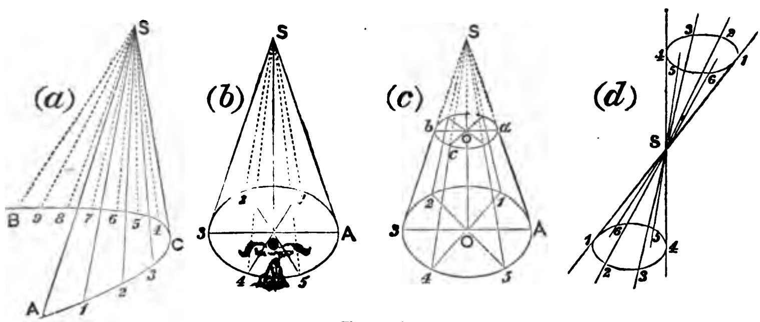

FIG. 304.

PROPOSITION I.

510. Theorem.—*Any section of a pyramid made by a plane parallel to its base is a polygon similar to the base.*

Dem.—The section *abcde* of the pyramid S-ABCDE, made by a plane parallel to ABCDE, is similar to ABCDE.

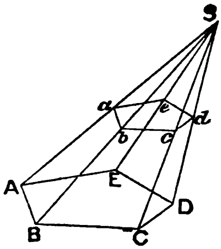

Fig. 305.

Since AB and *ab* are intersections of two parallel planes by a third plane, they are parallel (?). So also *bc* is parallel to BC, *cd* to CD, etc. Hence, angle $b =$ B, $c =$ C, etc. (?), and the polygons are mutually equiangular. Again, *ab* : AB :: S*b* : SB, and *bc* : BC :: S*b* : SB (?). Hence, *ab* : *bc* :: AB : BC (?). In like manner, we can show that *bc* : *cd* :: BC : CD, etc. Therefore, *abcde* and ABCDE are mutually equiangular, and have their corresponding sides proportional, and are consequently similar. Q. E. D.

PROPOSITION II.

511. Theorem.*—If two pyramids of the same altitude are cut by planes equally distant from and parallel to their bases, the sections are to each other as the bases.*

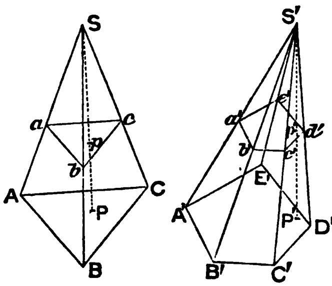

Fig. 306.

Dem.—Let S-ABC and S'-A'B'C'D'E' be two pyramids of the same altitude, cut by the planes *abc* and *a'b'c'd'e'*, parallel to and at equal distances from their bases; then is *abc* : *a'b'c'd'e'* :: ABC : A'B'C'D'E'.

For, conceive the bases in the same plane. Let SP = S'P' be the common altitude, and Sp = S'p' the distances of the cutting planes from the vertex. We have

$$\text{ABC} : abc :: \overline{\text{AB}}^2 : \overline{ab}^2 :: \overline{\text{SP}}^2 : \overline{\text{S}p}^2 \text{ (?)}.$$

$$\text{Also, A'B'C'D'E'} : a'b'c'd'e' :: \overline{\text{A'B'}}^2 : \overline{a'b'}^2 :: \overline{\text{S'P'}}^2 : \overline{\text{S'}p'}^2 \text{ (?)}.$$

Whence, as SP = S'P', and Sp = S'p' (?), we have

abc : *a'b'c'd'e'* :: ABC : A'B'C'D'E' (?). Q. E. D.

512. Cor.—*If the bases are equivalent, the sections are also equivalent.*

PROPOSITION III.

513. Theorem.*—The area of the lateral surface of a right pyramid is equal to the perimeter of the base multiplied by one-half the slant height.*

Dem.—The faces of such a pyramid are equal isosceles triangles (?), whose common altitude is the slant height of the pyramid (?). Hence, the area of

these triangles is the product of one-half the slant height into the sum of their bases. But this is the lateral surface of the pyramid. (See the third cut in *Fig.* 303.)

514. COR.—*The area of the lateral surface of the frustum of a right pyramid is equal to the product of its slant height into half the sum of the perimeters of its bases.*

The student will be able to give the proof. It is based upon (*325*) and definitions.

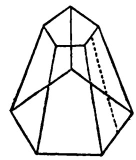

FIG. 307.

PROPOSITION IV.

515. Theorem.—*The area of the convex surface of a cone of revolution (a right cone with a circular base) is equal to the product of the circumference of its base and one-half its slant height,* i. e., πRH′, R *being the radius of the base, and* H′ *the slant height.*

DEM.—In the circle which forms the base of the cone, conceive a regular polygon inscribed, as *abcde*. Joining the vertices of the angles of this polygon with the vertex of the cone, there will be constructed a right pyramid inscribed in the cone. Now, if the arcs subtended by the sides of this polygon are bisected, and these again bisected, etc., and at every step a right pyramid conceived as inscribed, it will *always* remain true that the lateral surface of the pyramid is the perimeter of its base into half its slant height. But, as the number of faces of the pyramid is increased, the perimeter of the base approaches the circumference of the base of the cone, the slant height of the pyramid approaches the slant height of the cone, and the lateral surface of the pyramid approaches the convex surface of the cone. Hence, *at* the limit we still have the same expression for the area of the convex surface, that is, the circumference of the base multiplied by half the slant height. Finally, if R is the radius of the base, its circumference is 2πR, and H′ being the slant height, we have for the area of the convex surface $2\pi\text{R} \times \frac{1}{2}\text{H}'$, or πRH′.

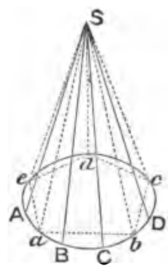

FIG. 308.

516. COR. 1.—*The area of the convex surface of a cone is also equal to the product of the slant height into the circumference of the circle parallel to the base, and midway between the base and vertex.*

This follows directly from the fact that the radius of the circle midway between the base and vertex is one-half the radius of the base, *i. e.*, $\frac{1}{2}$R, whence its circumference is πR. Now, $\pi\text{R} \times \text{H}'$ is the area of the convex surface, by the proposition.

517. COR. 2.—*The area of the convex surface of the frustum of a cone is equal to the product of its slant height into half the sum of the circumferences of its bases;* i. e., π (R + r) H′, R *and* r *being the radii of its bases, and* H′ *its slant height.*

From the corresponding property of the frustum of a pyramid, the student will be able to deduce the fact that $\frac{1}{2}(2\pi R + 2\pi r)$ H′, or $\pi (R + r)$ H′, is the area of this surface.

518. COR. 3.—*The area of the convex surface of the frustum of a cone is equal to the product of its slant height into the circumference of the circle midway between the bases.*

The radius of the circle midway between the bases is $\frac{1}{2}(r + R)$, whence its circumference is $\pi (r + R)$. Now, $\pi (r + R) \times H'$ is the area of the convex surface of the frustum, by the preceding corollary.

PROPOSITION V.

519. Theorem.—*Two pyramids having equivalent bases and the same altitudes are equivalent,* i. e., *equal in volume.*

DEM.—Let S-ABCD and S′-A′B′C′D′E′ be two pyramids having the same altitudes, and base ABCD equivalent to base A′B′C′D′E′, *i. e.*, equal in area; then is pyramid S-ABCD equivalent to S′-A′B′C′D′E′, *i. e.*, equal in volume.

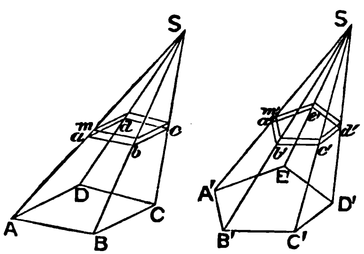

FIG. 309.

For, conceive the bases to be in the same plane, and a plane to start from coincidence with the plane of the bases, and move toward the vertices, remaining all the time parallel to the bases. At every stage of its progress the sections are equivalent, and as the plane reaches both vertices at the same time, by reason of the common altitude, it is evident that the volumes are equal.

Or, if desired, we may consider the two pyramids as divided into an equal number of infinitely thin *laminæ* parallel to the bases. Each lamina in one has its corresponding equivalent lamina in the other; hence the sum of all the *laminæ* in one equals the sum of all the *laminæ* in the other; *i. e.*, the pyramids are equivalent.

PROPOSITION VI.

520. Theorem.—*The volume of a triangular pyramid is equal to one-third the product of its base and altitude.*

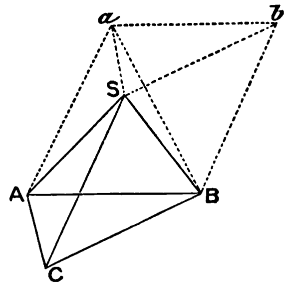

FIG. 310.

DEM.—Let S-ABC be a triangular pyramid, whose altitude is H*; then is the volume equal to $\frac{1}{3}$ H × *area* ABC.

For, through A and B draw A*a* and B*b* parallel to SC; and through S draw S*a* and S*b* parallel to CA and CB, and join *a* and *b*; then S*ab*-ABC is a prism with its bases equal to the base of the pyramid. Now, the solid added to the given pyramid is a quadrangular pyramid with *ab*BA as its base, and its vertex at S. Divide this into two triangular pyramids by drawing *a*B and passing a plane through SB and *a*B. These triangular pyramids are equivalent, since they have equal bases *a*AB and *ab*B and a common altitude, the vertices of both being at S. Again, S-*ab*B may be considered as having *ab*S (equal to ABC) as its base, and the altitude of the first pyramid (equal to the altitude of the prism) for its altitude, and hence as equivalent to the given pyramid. Therefore S-ABC is one third of the prism S*ab*-ABC. But the volume of the prism is H × *area* ABC. Therefore the volume of the pyramid S-ABC is $\frac{1}{3}$ H × *area* ABC. Q. E. D.

521. COR. 1.—*The volume of any pyramid is equal to one-third the product of its base and altitude.*

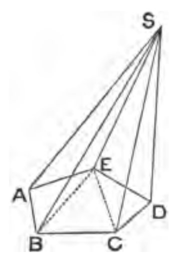

FIG. 311.

DEM.—Since any pyramid can be divided into triangular pyramids by passing planes through any one edge, as SE, and each of the other edges not adjacent, as SB and SC, the volume of the pyramid is equal to the sum of the volumes of several triangular pyramids having the same altitude as the given pyramid, and the sum of whose bases is the base of the given pyramid. Hence the truth of the corollary.

522. COR. 2.—*Pyramids having equivalent bases are to each other as their altitudes; such as have equal altitudes are to each other as their bases; and, in general, pyramids are to each other as the products of their bases and altitudes.*

* Not drawn in the figure, lest it might confuse.

PROPOSITION VII.

523. Theorem.—*The volume of the frustum of a triangular pyramid is equal to the volume of three pyramids of the same altitude as the frustum, and whose bases are the upper base, the lower base, and a mean proportional between the two bases of the frustum.*

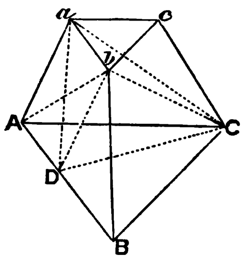

FIG. 312

DEM.—Let *abc*-ABC be the frustum of a triangular pyramid. Through *ab* and C pass a plane cutting off the pyramid C-*abc*. This has for its base the upper base of the frustum, and for its altitude the altitude of the frustum. Again, draw A*b*, and pass a plane through A*b* and *b*C, cutting off the pyramid *b*-ABC, which has the same altitude as the frustum, and for its base the lower base of the frustum. There now remains a third pyramid, *b*-AC*a*, to be examined. Through *b* draw *b*D parallel to *a*A, and draw DC and *a*D. The pyramid D-AC*a* is equivalent to *b*-AC*a*, since it has the same base and the same altitude. But the former may be considered as having ADC for its base, and the altitude of the frustum for its altitude, *i. e.*, as pyramid *a*-ADC. We are now to show that ADC is a mean proportional between *abc* and ABC.

$$ABC : abc :: \overline{AB}^2 : \overline{ab}^2 :: \overline{AB}^2 : \overline{AD}^2 \text{ (?)}.$$

Also, $ABC : ADC :: AB : AD$ (?);

whence $\overline{ABC}^2 : \overline{ADC}^2 :: \overline{AB}^2 : \overline{AD}^2$ (?).

By equality of ratios, $ABC : abc :: \overline{ABC}^2 : \overline{ADC}^2$;

whence $\overline{ADC}^2 = abc \times ABC$, *i. e.*, ADC is a mean proportional between the upper and lower bases of the frustum.

524. COR.—*The volume of the frustum of any pyramid is equal to the volume of three pyramids having the same altitude as the frustum, and for bases, the upper base, the lower base, and a mean proportional between the bases of the frustum.*

For, the frustum of any pyramid is equivalent to the corresponding frustum of a triangular pyramid of the same altitude and an equivalent base (?); and the bases of the frustum of the triangular pyramid being both equivalent to the corresponding bases of the given frustum, a mean proportional between the triangular bases is a mean proportional between their equivalents.

PROPOSITION VIII.

525. Theorem.—*The volume of a cone of revolution is equal to one-third the product of its base and altitude;* i. e., $\frac{1}{3}\pi R^2H$, R *being the radius of the base and* H *the altitude.*

DEM.—This follows from the volume of a pyramid, by a course of reasoning precisely the same as in (*515*). The volume of a pyramid being equal to one-third the product of the base and altitude, and the cone being the limit of the pyramid, the volume of the cone is one-third the product of its base and altitude. Now, R being the radius of the base of a cone of revolution, the base (area of) is πR^2, whence $\frac{1}{3}\pi R^2 H$ is the volume, H being the altitude.

526. COR. 1.—*The volume of any cone is equal to one-third the product of its base and altitude.*

527. COR. 2.—*The volume of the frustum of a cone is equal to the volume of three cones having the same altitude as the frustum, and for bases, the upper base, the lower base, and a mean proportional between the two bases of the frustum.*

The truth of this appears from the fact that the frustum of a cone is the limit of the frustum of a pyramid.

PROPOSITION IX.

528. Theorem.—*The lateral surfaces of similar right pyramids are to each other as the squares of their homologous edges, their slant heights, and their altitudes;* i. e., *as the squares of any two homologous dimensions.*

DEM.—Let A and a be homologous sides of the bases of two similar right pyramids, H' and h' their slant heights, H and h their altitudes, and P and p the perimeters of their bases; then—

(1) $P : p :: A : a$, because the bases are similar polygons;
(2) $A : a :: H' : h'$, because the faces are similar triangles;
(3) $H' : h' :: H : h$ (?).

Whence, $P : p :: H' : h'$;
and, as $\frac{1}{2}H' : \frac{1}{2}h' :: H' : h'$,
multiplying, we have $\frac{1}{2}P \times H' : \frac{1}{2}p \times h' :: H'^2 : h'^2 :: A^2 : a^2 :: H^2 : h^2$. But $\frac{1}{2}P \times H'$ and $\frac{1}{2}p \times h'$ are the areas of the lateral surfaces.

PROPOSITION X.

529. Theorem.—*The convex surfaces of similar cones of revolution are to each other as the squares of their slant heights, the radii of their bases, and their altitudes;* i. e., *as the squares of any two homologous dimensions.*

DEM.—Let H' and h' be the slant heights of two similar cones of revolution, R and r the radii of their bases, and H and h their altitudes; their convex surfaces are $\pi RH'$ and $\pi rh'$. Now, since the cones are similar $R : r :: H' : h'$.

Multiplying the terms of this proportion by the corresponding terms of $\pi H' \cdot \pi h' :: H' : h'$, we have—

$$\pi RH' : \pi rh' :: H'^2 : h'^2.$$

Hence the convex surfaces are as the squares of the slant heights, and since $R : r :: H' : h' :: H : h$ (?), $R^2 : r^2 :: H'^2 : h'^2 :: H^2 : h^2$; and consequently $\pi RH' : \pi rh' :: R^2 : r^2 :: H^2 : h^2$.

PROPOSITION XI.

530. Theorem.—*The volumes of similar pyramids are to each other as the cubes of their homologous dimensions.*

DEM.—Letting A and a be homologous sides of the bases of two similar pyramids, B and b their bases, and H and h their altitudes, the student should be able to give the reasons for the following proportions:

$$B : b :: A^2 : a^2 :: H^2 : h^2.$$

$$\tfrac{1}{3}H : \tfrac{1}{3}h :: A : a :: H : h.$$

Whence $\tfrac{1}{3}BH : \tfrac{1}{3}bh :: A^3 : a^3 :: H^3 : h^3$. Q. E. D.

PROPOSITION XII.

531. Theorem.—*The volumes of similar cones are to each other as the cubes of their altitudes, or as the cubes of the radii of their bases.*

DEM. R and r being the radii of their bases, and H and h their altitudes,

$$R^2 : r^2 :: H^2 : h^2 \text{ (?), and } R^3 : r^3 :: H^3 : h^3.$$

Also, $\tfrac{1}{3}\pi H : \tfrac{1}{3}\pi h :: H : h$.

Multiplying, $\tfrac{1}{3}\pi R^2H : \tfrac{1}{3}\pi r^2h :: H^3 : h^3$, or as $R^3 : r^3$. Q. E. D.

EXERCISES.

1. What is the area of the lateral surface of a right hexagonal pyramid whose base is inscribed in a circle whose diameter is 20 feet, the altitude of the pyramid being 8 feet? What is the volume of this pyramid?

2. What is the area of the lateral surface of a right pentagonal pyramid whose base is inscribed in a circle whose radius is 6 yards, the slant height of the pyramid being 10 yards? What is the volume of this pyramid?

3. How many quarts will a can contain, whose entire height is 10 inches, the body being a cylinder 6 inches in diameter and $6\frac{1}{2}$ inches

high, and the top a cone? How much tin does it take to make such a can, allowing nothing for waste and the seams?

4. If very fine dry sand is piled upon a smooth horizontal surface, without any lateral support, the angle of slope (*i. e.*, the angle of inclination of the sloping side of the pile with the plane) is about 31°. Suppose two circles be drawn on the floor, one 4 feet in diameter and the other 3, and sand piles be made as large as possible on these circles as bases, no other support being given. What is the relative magnitude of the piles?

5. In the case of sand piles, as given in the last example, the ratio of the radius of the base to the altitude of the pile is $\frac{5}{3}$. How many cubic feet in each of the above piles?

6. The frustum of a pyramid was 72 feet square at the lower base and 48 at the upper; and its altitude was 60 feet. What was the lateral surface? What the volume?

THE STUDENT SHOULD FURNISH A SYNOPSIS OF EACH SECTION AT ITS CLOSE.

SECTION V.

OF THE SPHERE.*

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532. A Sphere is a solid bounded by a surface every point in which is equally distant from a point within called the *Centre.* The distance from the centre to the surface is the *Radius,* and a line passing through the centre and limited by the surface is a *Diameter.* The diameter is equal to twice the radius.

* A spherical blackboard is almost indispensable in teaching this section, as well as in teaching Spherical Trigonometry. A sphere about 2 feet in diameter, mounted on a pedestal, and having its surface slated or painted as a blackboard, is what is needed. It can be obtained of the manufacturers of school apparatus, or made in any good turning-shop.

CIRCLES OF THE SPHERE.

PROPOSITION I.

533. *Theorem.*—*Every section of a sphere, made by a plane, is a circle.*

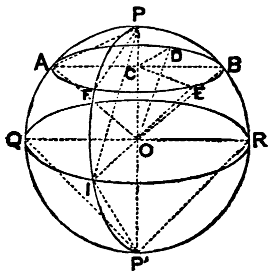

FIG. 313.

DEM.—Let AFEBD be a section of a sphere whose centre is O, made by a plane; then is it a circle.

For, let fall from the centre O a perpendicular upon the plane AFEBD, as OC, and draw CA, CD, CE, CB, etc., lines of the plane, from the foot of the perpendicular to any points in which the plane cuts the surface of the sphere. Join these points with the centre, O, of the sphere. Now, OA, OD, OB, OE, etc., being radii, are equal; whence, CA, CD, CB, CE, etc., are equal; *i. e.*, every point in the line of intersection of a plane and surface of a sphere is equally distant from a point in this plane. Hence, the intersection is a circle. Q. E. D.

534. DEF.—A circle made by a plane not passing through the centre is a *Small Circle;* one made by a plane passing through the centre is a *Great Circle.*

535. COR. 1.—*A perpendicular from the centre of a sphere, upon any small circle, pierces the circle at its centre;* and, conversely, *a perpendicular to a small circle at its centre passes through the centre of the sphere.*

536. DEF.—A diameter perpendicular to any circle of a sphere is called the *Axis* of that circle. The extremities of the axis are the *Poles* of the circle.

537. COR. 2.—*The pole of a circle is equally distant from every point in its circumference.*

The student should be able to give the reason.

538. COR. 3.—*Every circle of a sphere has two poles, which, in case of a great circle, are equally distant from every point in the circumference of the circle; but, in case of a small circle, one pole is nearer any point in the circumference than the other pole is.*

539. COR. 4.—*A small circle is less as its distance from the centre of the sphere is greater.*

For, its diameter, being a chord of a great circle, is less as it is farther from the centre of the great circle, which is also the centre of the sphere.

540. COR. 5.—*All great circles of the same sphere are equal,* their radii being the radius of the sphere.

PROPOSITION II.

541. ***Theorem.***—*Any great circle divides the sphere into two equal parts called Hemispheres.*

DEM.—Conceive a sphere as divided by a great circle, *i. e.*, by a plane passing through its centre, and let the great circle be considered as the base of each portion. These bases being equal, reverse one of the portions and conceive its base placed in the base of the other, the convex surfaces being on the same side of the common base. Since the bases are equal circles, they will coincide, and since every point in the convex surface of each portion is equally distant from the centre of the common base, the convex surfaces will coincide. Therefore, the portions coincide throughout, and are consequently equal. Q. E. D.

PROPOSITION III.

542. ***Theorem.***—*The intersection of any two great circles of a sphere is a diameter of the sphere.*

DEM.—The intersection of two planes is a straight line; and in the case of the two great circles, as they both pass through the centre of the sphere, this is one point of their intersection. Hence, the intersection of two great circles of a sphere is a straight line which passes through the centre. Q. E. D.

543. COR.—*The intersections on the surface of a sphere of two circumferences of great circles are a semi-circumference, or* 180°, *apart, since they are at opposite extremities of a diameter.*

DISTANCES ON THE SURFACE OF A SPHERE.

544. Distances on the surface of a sphere are always to be understood as measured on the arc of a great circle, unless it is otherwise stated.

PROPOSITION IV.

545. Theorem.—*The distances, measured on the surface of a sphere, from a pole to all points in the circumference of a circle of which it is the pole, are equal.*

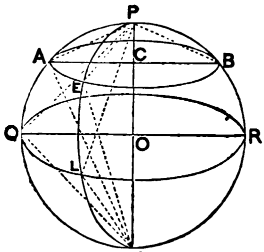

FIG. 314.

DEM.—Let P be a pole of the small circle AEB; then are the arcs PA, PE, PB, etc., which measure the distances from P to any points in the circumference of circle AEB, equal. For, by (*537*), the straight lines AP, PE, PB, etc., are equal, and these equal chords subtend equal arcs, as arc PA, arc PE, arc PB, etc., the great circles of which these lines are chords and arcs being equal (*540*). Thus, for like reasons, arc P'QA = arc P'LE = arc P'RB, etc.

546. COR.—*The distance from the pole of a great circle to any point in the circumference of the circle is a quadrant (a quarter of a circumference).*

Since the poles are 180° apart (being the extremities of a diameter), PAQP' = PELP' = a semicircumference. But, in case of a great circle, chord PL = chord P'L (= chord PQ = chord P'Q), whence arc PEL = arc P'L = arc PAQ = arc P'Q. Hence, each of these arcs is a quadrant.

FIG. 315.

547. SCH.—By means of the facts demonstrated in this proposition and corollary, we are enabled to draw arcs of small and great circles, in the surface of a sphere, with nearly the same facility as we draw arcs and lines in a plane. Thus, to draw the small circle AEB, we take an arc equal to PE, and placing one end of it at P, cause a pencil held at the other end to trace the arc AEB, etc. To describe the circumference of a great circle, a quadrant must be used for the arc. By bending a wire into an arc of the circle, and making a loop in each end, a wooden pin can be put through one loop and a crayon through the other, and an arc drawn as represented in the figure.

PROPOSITION V.

548. Problem.—*To pass a circumference of a great circle through any two points on the surface of a sphere.*

SOLUTION.—Let A and B be two points on the surface of a sphere, through which it is proposed to pass a circumference of a great circle. From B as a pole, with an arc equal to a quadrant, strike an arc *on*, as nearly where the pole of tne circle passing through A and B lies, as may be determined by inspection. Then, from A, with the same arc, strike an arc *st* intersecting *on* at P. Now, P is the pole of the great circle passing through A and B. Hence, from P as a pole, with a quadrant arc draw a circle; it will pass through A and B, and will be a great circle, since its pole is a quadrant's distance from its circumference. [The student should make the construction on the spherical blackboard.]

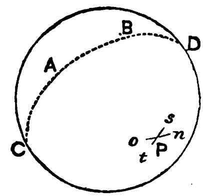

FIG. 316.

549. COR. 1.—*Through any two points on the surface of a sphere, one great circle* can always be made to pass, and only one, except when the two points are at the extremities of the same diameter, in which case an infinite number of great circles can be passed through the two points.*

Since the arcs *on* and *st* are arcs of great circles, the circumferences of which they form parts will intersect also on the opposite side of the sphere, at a distance of a semicircumference from P. But these two points are poles of the *same* great circle. Now, as the two great circles can intersect at no other points, there can be only one great circle passed through A and B. But if the two given points were at the extremities of the same diameter, as at D and C, the arcs *st* and *on* would coincide, and *any* point in this circumference being taken as a pole, great circles can be drawn through D and C. [The student should trace the work on the spherical blackboard.]

550. SCH.—The truth of the corollary is also evident from the fact that three points not in the same straight line determine the position of a plane. Thus A, B, and the centre of the sphere, fix the position of one, and only one, great circle passing through A and B. Moreover, if the two given points are at the extremities of the same diameter, they are in the same straight line with the centre of the sphere, whence an infinite number of planes can be passed through them and the centre. The meridians on the earth's surface afford an example, the poles (of the equator) being the given points.

551. COR. 2.—*If two points in the circumference of a great circle of a sphere, not at the extremities of the same diameter, are at a quadrant's distance from a point on the surface, that point is the pole of the circle.*

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* The word circle may be understood to refer either to the circle proper, or to its circumference. The word is in constant use in the higher mathematics, in the latter sense.

PROPOSITION VI.

552. Theorem.—*The shortest distance on the surface of a sphere, between any two points in that surface, is measured on the arc less than a semicircumference of the great circle which joins them.*

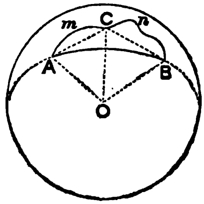

FIG. 317.

DEM.—Let A and B be any two points in the surface of a sphere, AB the arc of a great circle joining them, and $AmCnB$ any other path in the surface between A and B; then is arc AB less than $AmCnB$.

Let C be any point in $AmCnB$, and pass the arcs of great circles through A and C, and B and C. Join A, B, and C with the centre of the sphere. The angles AOB, AOC, and COB form the facial angles of a triedral, of which angles the arcs AB, AC, and CB are the measures. Now, angle AOB < AOC + COB (*434*); whence arc AB < arc AC + arc CB, and the path from A to B is less on arc AB than on arcs AC, CB. In like manner, joining any point in AmC with A and C by arcs of great circles, their sum would be greater than AC. So, also, joining any point in CnB with C and B, the sum of the arcs would be greater than CB. As this process is indefinitely repeated, the path from A to B on the arcs of the great circles will continually increase, and also continually approximate the path $AmCnB$. Hence, arc AB is less than the path $AmCnB$. Q. E. D.

553. COR.—*The least arc of a circle of a sphere joining any two points in the surface, is the arc less than a semicircumference of the great circle passing through the points; and the greatest arc is the circumference minus this least arc.*

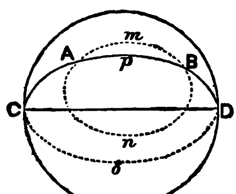

FIG. 318.

DEM.—Let $AmBn$ be any small circle passing through A and B, and $ABDoC$ the great circle. As shown above, $ApB < AmB$. Now, circumference $ABDoC$ > circumference $AmBn$ (*539*). Subtracting the former inequality from the latter, we have $BDoCA > BnA$. Q. E. D.

PROPOSITION VII.

554. Theorem.—*The shortest path on the surface of a hemisphere, from any point therein to the circumference of the great circle forming its base, is the arc less than a quadrant of a great circle perpendicular to the base, and the longest path, on any arc of a great circle, is the supplement of this shortest path.*

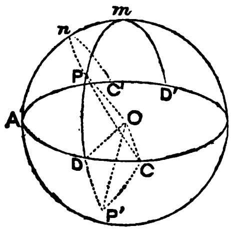

FIG. 319.

DEM.—Let P be a point in the surface of the hemisphere whose base is ACBC′, and DPmD′ an arc of a great circle passing through P and perpendicular to ADCBC′; then is PD the shortest path on the surface from P to circumference ADBC′, and PmD′ is the longest path from P to the circumference, measured on the arc of a great circle.

For, the shortest path from P to any point in circumference ADBC′ is measured on the arc of a great circle (*552*). Now, let PC be any oblique arc of a great circle. We will show that arc PD < arc PC. Produce PD until DP′ = PD; and pass a great circle through P′ and C. Draw the radii OP, OD, OC, and OP′. The triedrals O-PDC and O-P′DC have the facial angle POD = P′OD, they being measured by equal arcs, and the facial angle DOC common. Hence, as the included diedrals are equal, both being right, the triedrals are equal or symmetrical (*446*). In this case they are symmetrical, and the facial angle POC = P′OC; whence the arc PC = arc P′C. Finally, since PC + P′C > PP′, PC, the half of PC + P′C, is greater than PD, the half of PP′.

Secondly, PmD′ is the supplement of PD, and we are to show that it is greater than any other arc of a great circle from P to the circumference ADBC′. Let PnC′ be any arc of a great circle oblique to ADCBC′. Produce C′nP to C. Now CPnC′ is a semicircumference and consequently equal to DPmD′. But we have before shown that PD < PC, and subtracting these from the equals CPnC′ and DPmD′, we have PmD′ > PnC′.

555. COR.—*From any point in the surface of a hemisphere there are two perpendiculars to the circumference of the great circle which forms the base of the hemisphere; one of which perpendiculars measures the least distance to that circumference, and the other the greatest, on the arc of any great circle of the sphere.*

Thus PD and PmD′ are two perpendiculars from P upon the circumference ADBC′.

SPHERICAL ANGLES.

556. The angle formed by two arcs of circles of a sphere is conceived as the same as the angle included by the tangents to the arcs at the common point.

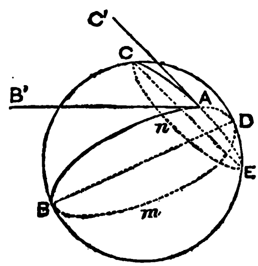

FIG. 320.

ILL.—Let AB and AC be two arcs of circles of the sphere, meeting at A; then the angle BAC is conceived as the same as the angle B′AC′, B′A being tangent to the circle BADm, and C′A to the circle CAEn.

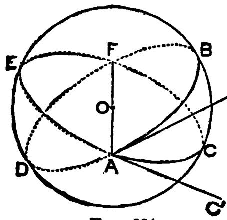

FIG. 321.

557. A Spherical Angle is the angle included by two arcs of *great circles.*

ILL.—BAC, *Fig.* 321, is a spherical angle, and is conceived as the same as the angle B′AC′, B′A and C′A being tangents to the *great circles* BADF and CAEF. [The student should not confound such an angle as BAC, *Fig.* 320, with a *spherical angle.*]

PROPOSITION VIII.

558. Theorem.—*A spherical angle is equal to the measure of the diedral included by the great circles whose arcs form the sides of the angle.*

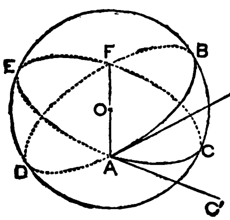

FIG. 322.

DEM.—Let BAC be any spherical angle, and BADF and CAEF the great circles whose arcs BA and CA include the angle; then is BAC equal to the measure of the diedral C-AF-B. For, since two great circles intersect in a diameter (***542***), AF is a diameter. Now B′A is a tangent to the circle BADF, that is, it lies in the same plane and is perpendicular to AO at A. In like manner C′A lies in the plane CAEF and is perpendicular to AO. Hence B′AC′ is the measure of the diedral C-AF-B (***425***). Therefore the spherical angle BAC, which is the same as the plane angle B′AC′, is equal to the measure of the diedral C-AF-B. Q. E. D.

559. COR. 1.—*If one of two great circles passes through the pole of the other, their circumferences intersect at right angles.*

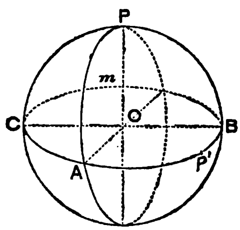

FIG. 323.

DEM.—Thus, P being the pole of the great circle CAB*m*, PO is its axis, and any plane passing through PO is perpendicular to the plane CAB*m* (***429***). Hence, the diedral B-AO-P is right, and the spherical angle PAB, which is equal to the measure of the diedral, is also right.

560. COR. 2.—*A spherical angle is measured by the arc of a great circle intercepted between its sides, and at a quadrant's distance from its vertex.*

Thus, the spherical angle CPA is measured by CA, PC and PA being quadrants. For, since PC is a quadrant, CO is perpendicular to PO, the edge of the diedral C-PO-A, and for a like reason AO is perpendicular to PO. Hence, COA is the measure of the diedral, and consequently CA, its measure, is the measure of the spherical angle CPA.

561. COR. 3.—*The angle included by two arcs of small circles is the same as the angle included by two arcs of great circles passing through the vertex and having the same tangents.*

Thus BAC = B″AC″. For the angle BAC is, by definition, the same as B′AC′, B′A and C′A being tangents to BA and CA. Now, passing planes through C′A, B′A, and the centre of the sphere, we have the arcs B″A, C″A, and B′A, C′A tangents to them. Hence, B″AC″ is the same as B′AC′, and consequently the same as BAC.

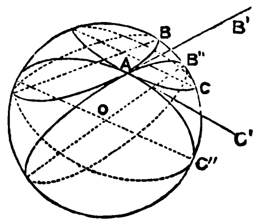

FIG. 324

562. SCH.—*To draw an arc of a great circle which shall be perpendicular to another; or, what is the same thing, to construct a right spherical angle.* Let it be required to erect an arc of a great circle perpendicular to CAB at A, *Fig.* 323. Lay off from A, on the arc CAB, a quadrant's distance, as AP′, and from P′ as a pole, with a quadrant describe an arc passing through A. This will be the perpendicular required.

In a similar manner we may let fall a perpendicular from any point in the surface, upon any arc of a great circle. To let fall a perpendicular from P upon the arc CAB, from P as a pole, with a quadrant describe an arc cutting CAB, as at P′. Then from P′ as a pole, with a quadrant describe an arc passing through P and cutting CAB, and it will be perpendicular to CAB. [The student should have practice in making these constructions on the sphere.]

PROPOSITION IX.

563. Problem.—*To pass the circumference of a small circle through any three points on the surface of a sphere.*

SOLUTION.—Let A, B, and C be the three points in the surface of the sphere through which we propose to pass the circumference of a circle. Pass arcs of great circles through the points, forming the spherical triangle ABC. Thus, to pass an arc of a great circle through B and C, from B as a pole, with a quadrant strike an arc as near as may be to the pole of the required circle; and from C as a pole, with the quadrant strike an arc intersecting the former, as at P; then is P the pole of a great circle passing through B and C (?). Hence, from P as a pole, with a quadrant pass an arc through B and C, and it will be the arc required (***551***). In like manner pass arcs through A and C, A and B. Now, bisect two of these arcs, as BC and AC, by arcs of great

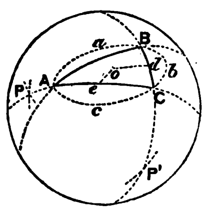

FIG. 325.

circles perpendicular to each. [The student will readily perceive how this is done.] The intersection of these perpendiculars, *o*, will be the pole of the small circle required (?). Then from *o*, as a pole, with an arc *o*B draw the circumference of a small circle: it will pass through A, B, and C (?), and hence is the circumference required.

OF TANGENT PLANES.

564. ***A Tangent Plane*** to a curved surface at a given point is the plane of two lines respectively tangent to two plane sections through the point.

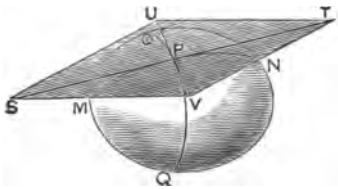

FIG. 326.

ILL.—Let P be a point in the curved surface at which we wish a tangent plane. Pass any two planes through the surface and the point P, and let OPQ and MPN represent the intersections of these planes with the curved surface. Draw UV and ST in the planes of the sections, and tangent to OPQ and MPN, at P. Then is the plane of UV and ST the tangent plane at P.

PROPOSITION X.

565. ***Theorem.***—*A tangent plane to a sphere is perpendicular to the radius at the point of tangency.*

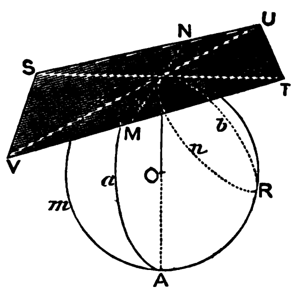

FIG. 327.

DEM.—Let P be any point in the surface of a sphere; pass two great circles, as P*a*A, etc., and P*m*AR, through P, and draw ST tangent to the arc *m*P, and UV tangent to the arc *a*P; then is the plane SVTU a tangent plane at P, and perpendicular to the radius OP. For, a tangent (as ST) to the arc *m*P is perpendicular to the radius of the circle, *i. e.*, to OP, and also a tangent (as VU) to the arc *a*P is perpendicular to the radius of *this* circle, *i. e.*, to OP. Hence, OP is perpendicular to two lines of the plane SVTU, and consequently to the plane of these lines (?). Q. E. D.

566. COR. 1.—*Every point in a tangent plane to a sphere, except the point of tangency, is without the sphere.*

For, OP, the perpendicular, is shorter than any line which can be drawn from O to any other point in the plane (?), hence any other point in the plane than P lies farther from the centre of the sphere than the length of the radius, and is, therefore, without the sphere.

567. COR. 2.—*A tangent through* P *to* ANY *circle of the sphere passing through this point, lies in the tangent plane.*

DEM.—Thus MN, tangent to the small circle P*n*R*b* through P, lies in the tangent plane. For, conceive the plane of the small circle extended till it intersects the tangent plane. This intersection is tangent to the small circle, since it touches it at one point, but cannot cut it; otherwise the tangent plane would have another point than P common with the surface of the sphere. But there can be only one tangent to a circle at a given point. Hence this intersection is MN, which is consequently in the tangent plane.

OF SPHERICAL TRIANGLES.

568. ***A Spherical Triangle*** is a portion of the surface of a sphere bounded by three arcs of great circles. In the present treatise these arcs will be considered as each less than a semicircumference.

The terms scalene, isosceles, equilateral, right angled, and oblique angled, are applied to spherical triangles in the same manner as to plane triangles.

PROPOSITION XI.

569. ***Theorem.***—*The sum of any two sides of a spherical triangle is greater than the third side, and their difference is less than the third side.*

DEM.—Let ABC be any spherical triangle; then is BC < BA + AC, and BC − AC < BA; and the same is true of the sides in any order. For, join the vertices A, B, and C, with the centre of the sphere, by drawing AO, BO, and CO. There is thus formed a triedral O-ABC, whose facial angles are measured by the sides of the triangle (*208*). Now, angle BOC < BOA + AOC (*434*), whence BC < BA + AC: and subtracting AC from both members, we have BC − AC < BA.

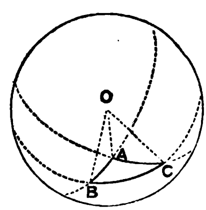

FIG. 328.

PROPOSITION XII.

570. Theorem.*—The sum of the sides of a spherical triangle may be anything between* 0 *and a circumference.*

DEM.—The sides of a spherical triangle are measures of the facial angles of a triedral whose vertex is at the centre of the sphere. Hence their sum may be anything between 0 and the measure of 4 right angles, as these are the limits of the sum of the facial angles of a triedral (***436***).

571. SCH.—As the sides of a spherical triangle are arcs, they can be measured in degrees. Hence, we speak of the side of a spherical triangle as 30°, 57°, 115° 10′, etc. In accordance with this, we say that the limit of the sum of the sides of a spherical triangle is 360°.

PROPOSITION XIII.

572. Theorem.*—The sum of the angles of a spherical triangle may be anything between two and six right angles.*

DEM.—The sum of the angles of a spherical triangle is the same as the sum of the measures of the diedrals of a triedral having its vertex at the centre of the sphere, as in (***569***). Now the limits of the sum of the measures of these diedrals are 2 and 6 right angles (***439***). Hence the sum of the angles of any spherical triangle may be anything between 2 and 6 right angles. Q. E. D.

573. SCH.—It will be observed, that the sum of the angles of a spherical triangle is not constant, as is the sum of the angles of a plane triangle. Thus, the sum of the angles of a spherical triangle may be 200°, 290°, 350°, 500°, anything between 180° and 540°.

574. DEF.—***Spherical Excess*** is the amount by which the sum of the angles of a spherical triangle exceeds the sum of the angles of a plane triangle; *i. e.*, it is the sum of the spherical angles $-180°$, or π.

ILL.—It is not difficult to observe the occasion of this *excess* in the case of the equilateral spherical triangle. Thus, let ABC be such a triangle. Conceive the plane triangle formed by the chords AB, AC, and CB. The sum of the angles of this plane triangle is 180°. But each angle of the spherical triangle is larger than the corresponding angle of the plane triangle. Thus, the spherical angle BAC is the same as the plane angle C′AB′, included between the tangents C′A and B′A, which are perpendicular to the edge of the diedral C-AO-B, and include its measuring angle. Now, CA and BA

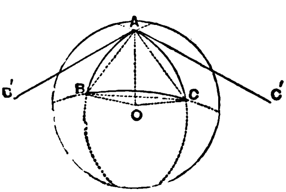

FIG. 329.

being different lines from C'A and B'A are oblique to the edge AO, and include an angle *less* than its measure, and consequently less than CAB. For a like reason the plane angle ACB < the spherical angle ACB, and plane angle ABC < spherical angle ABC. Moreover, it is easy to see that the inequality between any plane angle and the corresponding spherical angle increases as the chords BA and CA deviate more from the tangents. Whence we see why the sum of the angles of the spherical triangle is not a fixed quantity.

575. COR.—*A spherical triangle may have one, two, or even three right angles; and, in fact, it may have one, two, or three obtuse angles; since, in the latter case, the sum of the angles will not necessarily be greater than* 540°.

576. DEF.—***A Trirectangular Spherical Triangle*** is a spherical triangle which has three right angles.

PROPOSITION XIV.

577. *Theorem.*—*The trirectangular triangle is one-eighth of the surface of a sphere.*

DEM.—Pass three planes through the centre of a sphere, respectively perpendicular to each other. They will divide the surface into 8 trirectangular triangles, any one of which may be applied to any other. Thus, let ABA'B', ACA'C', and CBC'B' be the great circles formed by the three planes, mutually perpendicular to each other. The planes being perpendicular to each other the diedrals, as A-CO-B, C-BO-A, C-AO-B, etc., are right, and hence the angles of the 8 triangles formed are all right. Also, as AOB is a right angle, AB is a quadrant; as BOC is a right angle, CB is a quadrant, etc. Hence, each side of every triangle is a quadrant. Now any one triangle may be applied to any other. [Let the student make the application.] Hence the trirectangular triangle is one-eighth of the surface of a sphere. Q. E. D.

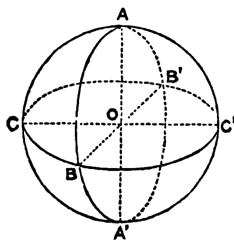

FIG. 330.

578. COR.—*The trirectangular triangle is equilateral and its sides are quadrants.*

PROPOSITION XV.

579. *Theorem.*—*In an isosceles spherical triangle the angles opposite the equal sides are equal;* and, conversely, *If two angles of a spherical triangle are equal, the triangle is isosceles.*

DEM.—Let ABC be an isosceles spherical triangle in which AB = AC; then angle ABC = ACB. For, draw the radii AO, CO, and BO, forming the edges of the triedral O-ABC. Now, since AB = AC, the facial angles AOC and AOB are equal, and the triedral is isosceles. Hence the diedrals A-OB-C and A-OC-B are equal (*442*), and consequently the spherical angles ABC and ACB are equal (*558*). Again, if angle ABC = angle ACB, side AC = side AB. For in the triedral O-ABC, the diedrals A-OB-C and A-OC-B are equal, whence the facial angles AOB and AOC are equal (*443*), and consequently the sides AB and AC which measure these angles.

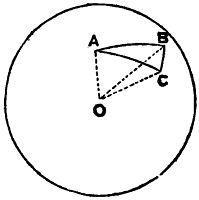

FIG. 331.

580. COR.—*An equilateral spherical triangle is also equiangular*; and, conversely, *If the angles of a spherical triangle are equal the triangle is equilateral.*

PROPOSITION XVI.

581. ***Theorem.***—*On the same or on equal spheres two isosceles triangles having two sides and the included angle of the one equal to two sides and the included angle of the other, each to each, can be superimposed, and are consequently equal.*

DEM.—In the triangles ABC and AB′C′, let AB = AC, AB′ = AC′; and let AB = AB′, BC = B′C′, and angle ABC = AB′C′; then can the triangle AB′C′ be superimposed upon ABC. For, since the triangles are isosceles, we have angle ABC = ACB, AB′C′ = AC′B′, and, as by hypothesis ABC = AB′C′, these four angles are equal each to each. For a like reason AB = AC = AB′ = AC′. Now, applying AC′ to its equal AB, the extremity A at A and C′ at B, with the angle B′ on the same side of AB as C, the convexities of the arcs AC′ and AB being the same, and in the same direction, the arcs will coincide. Then, as angle AC′B′ = ABC, C′B′ will take the direction BC, and since these arcs are equal by hypothesis, B′ will fall at C. Hence B′A will fall in CA, as only one arc of a great circle can pass between C and A, and the triangle AB′C′ is superimposed upon ABC; wherefore they are equal. [Let the student give the application when other parts are assumed equal.]

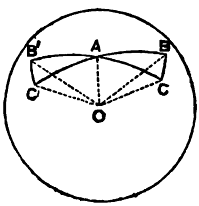

FIG. 332.

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582. ***Symmetrical Spherical Triangles*** are such as have the parts (sides and angles) of the one respectively equal to the parts of the other, but arranged in a different order, so that the triangles are not capable of superposition.

ILL.—In *Fig.* 333, ABC and A′B′C′ represent symmetrical spherical triangles. In these triangles A = A′, B = B′, C = C′, AC = A′C′, AB = A′B′, and BC = B′C′; nevertheless we cannot conceive one triangle superimposed upon the other. Thus, were we to make the attempt by placing A′B′ in its equal AB, A′ at A, and B′ at B, the angle C′ would fall on the opposite side of AB from C. Now, we cannot revolve A′C′B′ on AB (or its chord), and thus make the two coincide, for this would bring their convexities together. Nor can we make them coincide by reversing A′B′C′, and placing B′ at A, and A′ at B. For, although these two arcs will thus coincide, as the angle B′ is not equal to A, B′C′ will not fall in AC; and, again, if it did, C′ would not fall at C, since B′C′ and AC are not equal.

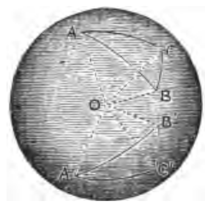

FIG. 333.

But, considering the triangles ABC and A′B′C′ in *Fig.* 334, in which A = A′, B = B′, C = C′, AC = A′C′, AB = A′B′, and BC = B′C′, we can readily conceive the latter as superimposed upon the former. [The student should make the application.] Now, the two triangles are equal in each case, as will subsequently appear of the former. Such triangles as those in *Fig.* 333 are called *symmetrically equal*, while the latter are said to be equal by *superposition*.

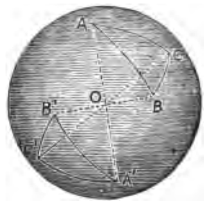

FIG. 334.

Fig. 335 represents the same triangles as *Fig.* 334, and exhibits a complete projection* of the semicircumferences of which the sides of the triangles are arcs. The student should become perfectly familiar with it, and be able to draw it readily. Thus, *a*AB*b* is the projection of the semicircumference of which AB is an arc, *a*AC*c* of the semicircumference of which AC is an arc, etc., etc.

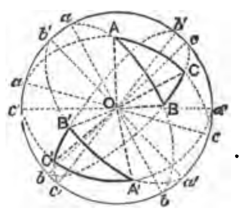

FIG. 335.

PROPOSITION XVII.

583. *Theorem.*—*Symmetrical spherical triangles are equivalent.*

* To understand what is meant by the projection of these lines, conceive a hemisphere with its base on the paper, and represented by the circle *abc*, and all the arcs raised up from the paper as they would be on the surface of such a hemisphere. Thus, considering the arc *a*AB*b*, the ends *a* and *b* would be in the paper just where they are, but the rest of the arc would be off the paper, as though you could take hold of B and raise it from the paper while *a* and *b* remain fixed. The lines in the figure are representations of lines on the surface of such a hemisphere, as they would appear to an eye situated in the axis of the circle *abc*, and at an infinite distance from it; that is, just as if each point in the lines dropped *perpendicularly* down upon the paper. Arcs of great circles perpendicular to the base are projected in straight lines passing through the centre, and oblique arcs are projected in ellipses. See *Spherical Trigonometry* (*97-109*).

DEM.—Let ABC and A′B′C′ be two symmetrical spherical triangles, with AB = A′B′, AC = A′C′, BC = B′C′, A = A′, B = B′, and C = C′; then are they equivalent.

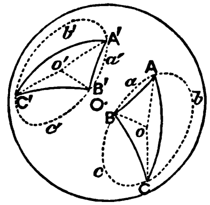

FIG. 336.

For, pass circumferences of small circles through the vertices A, B, C and A′, B′, C′, as *abc* and *a′b′c′*, of which *o* and *o′* are the poles. [The student should execute this on the spherical blackboard.] Now, by reason of the mutual equality of the sides, the *chord* AC = *chord* A′C′, *chord* AB = *chord* A′B′, and *chord* BC = *chord* B′C′, and as the small circles are circumscribed about the equal *plane* triangles ABC and A′B′C′, these circles are equal. Hence, *o*A = *o′*A′ = *o*B = *o′*B′ = *o*C = *o′*C′. The triangle A*o*B is therefore equal to A′*o′*B′, B*o*C = B′*o′*C′, and A*o*C = A′*o′*C′. [The student should make the application of these equal triangles.] Hence, ABC is equivalent to A′B′C′, as the two are composed of equal parts.

If the poles of the small circles fell without the given triangles, ABC would be equivalent to the sum of two of the partial triangles minus the third.

PROPOSITION XVIII.

584. Theorem.—*On the same or equal spheres, two spherical triangles having two sides and the included angle of the one equal to two sides and the included angle of the other, each to each, are equal, or symmetrical and equivalent.*

FIG. 337.

DEM.—Let ABC and A′B′C′, *Fig.* 337, be two spherical triangles having AB = A′B′, AC = A′C′, and A = A′. In this case, as the parts are similarly arranged, by placing AC in its equal A′C′, AB will fall in its equal A′B′ (as A = A′), and the two triangles will coincide. Hence, they are equal. Again, let the two triangles be ABC and A′B′C′, *Fig.* 338, in which AB = A′B′, AC = A′C′, and A = A′, the parts not being similarly arranged, so that the triangles are incapable of superposition. Thus, if AB is placed in its equal A′B′, A at A′, and B at B′, C and C′ will fall on *opposite* sides of AB. We may, however, construct ABC, *Fig.* 337, symmetrical with A′B′C′ in this figure, and apply ABC of *Fig.* 338 to it, and find that they coincide. Now, ABC, *Fig.* 337, and A′B′C′, *Fig.* 338, are equivalent (***583***); hence ABC, *Fig.* 338, is equivalent to A′B′C′, *Fig.* 338.

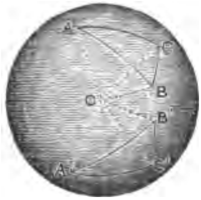

FIG. 338.

585. SCH.—This proposition is virtually the same as (***446***) concerning triedrals. Thus, in *Fig.* 337, drawing the radii AO, BO, CO, A′O, B′O, and C′O, two

triedrals are formed, having the facial angle AOB = A′OB, AOC = A′OC′, the included diedrals equal, and the parts similarly disposed, whence the triedrals are equal. In like manner the triedral O-ABC, *Fig.* 338, is symmetrical and equivalent to O-A′B′C′, *Fig.* 338. Hence, in either case, all the parts of one spherical triangle are equal to all the parts of the other, each to each.

PROPOSITION XIX.

586. Theorem.*—On the same, or on equal spheres, two spherical triangles having two angles and the included side of the one equal to two angles and the included side of the other, each to each, are equal, or symmetrical and equivalent.*

DEM.—Using the same triangles as in the preceding proposition, the student should be able to make the application directly, when the parts are similarly disposed; and when not similarly disposed, he should be able to show that ABC, of *Fig.* 338, can be applied to ABC, *Fig.* 337, symmetrical with A′B′C′, *Fig.* 338.

587. SCH.—This proposition is also virtually the same as (***447***) concerning triedrals. Let the student point out the identity.

PROPOSITION XX.

588. Theorem.*—On the same, or on equal spheres, if two spherical triangles have two sides of the one equal to two sides of the other, each to each, and the included angles unequal, the third sides are unequal, and the greater third side belongs to the triangle having the greater included angle.* Conversely, *If the two sides are equal, each to each, and the third sides unequal, the angles included by the equal sides are unequal, and the greater belongs to the triangle having the greater third side.*

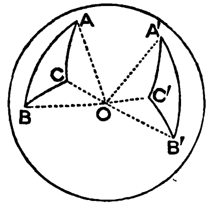

FIG 339.

DEM.—In the triangles ABC and A′B′C′, let AB = A′B′, AC = A′C′, and A > A′; then is BC > B′C′. For, join the vertices with the centre, forming the two triedrals O-ABC and O-A′B′C′. In these triedrals AOB = A′OB′, AOC = A′OC′, being measured by equal arcs; and C-AO-B > C′-A′O-B′, having the same measures as A and A′ (***558***). Hence COB > C′OB′ (***449***). Therefore CB, the measure of COB, is greater than C′B′, the measure of C′OB′.

In like manner, the same sides of the triangles, and consequently the same facial angles of the triedrals, being granted equal, and

BC > B′C′, A > A′. For, BC being greater than B′C′, COB > C′OB′; whence B-AO-C > B′-A′O-C′ (*450*), or A is greater than A′.

PROPOSITION XXI.

589. Theorem.—*On the same, or on equal spheres, two spherical triangles having the sides of the one respectively equal to the sides of the other, or the angles of the one respectively equal to the angles of the other, are equal, or symmetrical and equivalent.*

Dem.—The sides of the triangles being equal, the facial angles of the triedrals at the centre are equal, whence the triedrals are equal or symmetrical (*451*). Consequently the angles of the triangles are equal, and the triangles are equal, or symmetrical and equivalent.

Again, the triangles being mutually equiangular, the triedrals have their diedrals mutually equal; whence the triedrals are equal or symmetrical (*452*). Therefore, the sides of the triangles are mutually equal, and the triangles are equal, or symmetrical and equivalent. (See *Figs.* 333, 334.)

PROPOSITION XXII.

590. Theorem.—*On spheres of different radii, mutually equiangular triangles are similar* (not equal).

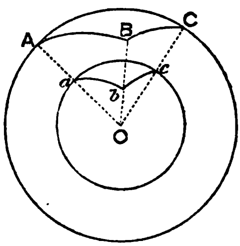

Fig. 340.

Dem.—Let O be the common centre of two unequal spheres; and let ABC be a spherical triangle on the surface of the outer. Draw the radii AO, BO, and CO, constructing the triedral O-ABC. Now, the intersections of these faces with the surface of the inner sphere will constitute a triangle which is mutually equiangular with ABC. Thus, A = *a*, B = *b*, and C = *c*, since in each case the corresponding diedrals are the same. From the similar sectors *a*O*b*, AOB, we have *ab* : AB :: *a*O : AO; and, in like manner, *ac* : AC :: *a*O : AO. Whence, *ab* : AB :: *ac* : AC. So, also, *ab* : AB :: *b*O : BO, and *bc* : BC :: *b*O : BO; whence, *ab* : AB :: *bc* : BC. Thus we see that ABC and *abc*, having their angles equal each to each, have also their sides proportional: therefore they are similar.

POLAR OR SUPPLEMENTAL TRIANGLES.

591. One triangle is polar to another when the vertices of one are the poles of the sides of the other. Such triangles are also

called *supplemental,* since the angles of one are the supplements of the sides opposite in the other, as will appear hereafter.

PROPOSITION XXIII.

592. Problem.—*Having a spherical triangle given, to draw its polar.*

SOLUTION.—Let ABC be the given triangle.* From A as a pole, with a quadrant strike an arc, as C′B′. From B as a pole, with a quadrant strike the arc C′A′; and from C, the arc A′B′. Then is A′B′C′ polar to ABC.

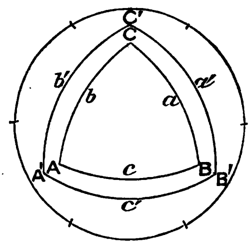

FIG. 341.

593. COR.—*If one triangle is polar to another,* conversely, *the latter is polar to the former;* i. e., *the relation is reciprocal.*

Thus, A′B′C′ being polar to ABC; reciprocally, ABC is polar to A′B′C′; that is, A′ is the pole of CB, B′ of AC, and C′ of AB. For every point in A′B′ is at a quadrant's distance from C, and every point in A′C′ is at a quadrant's distance from B. Hence, A′ is at a quadrant's distance from the two points C and B of CB, and is therefore its pole. [In like manner the student should show that B′ is the pole of AC, and C′ of AB.]

594. SCH.—By producing each of the arcs struck from the vertices of the given triangles sufficiently, *four* new triangles will be formed, viz., A′B′C′, QC′B′, PC′A′, and RA′B′. Only the first of these is called polar to the given triangle. It is easy to observe the relation of any of the parts of any one of the other three triangles to the parts of the polar. Thus, $QC' = 180° - b'$, $QB' = 180° - c'$, $QC'B' = 180° - B'C'A'$, $QB'C' = 180° - C'B'A'$, and $Q = A' = 180° - a$, as will appear hereafter.

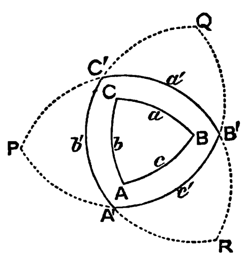

FIG. 342.

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* This should be executed on a sphere. Few students get clear ideas of polar triangles without it. Care should be taken to construct a variety of triangles as the given triangle, since the polar triangle does not always lie in the position indicated in the figure here given. Let the given triangle have one side considerably greater than 90°, another somewhat less, and the third quite small. Also, let each of the sides of the given triangle be greater than 90°.

PROPOSITION XXIV.

595. Theorem.—*Any* ANGLE *of a spherical triangle is the supplement of the* SIDE *opposite in its polar triangle; and any* SIDE *is the supplement of the* ANGLE *opposite in the polar triangle.*

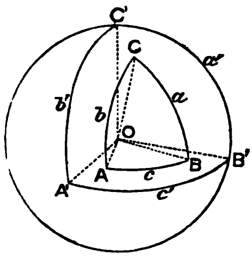

FIG. 343.

DEM.—Let ABC and A'B'C' be two spherical triangles polar to each other; and let the sides of each be designated as a, b, c, a', b', c', a being opposite A, a' opposite A', b opposite B, etc. Then $A = 180° - a'$, $B = 180° - b'$, $C = 180° - c'$, $a = 180° - A'$, $b = 180° - B'$, and $c = 180° - C'$.

For, join the vertices of the triangles with the centre of the sphere, thus forming the triedrals O-ABC, and O-A'B'C'. These triedrals are supplemental; for, A being the pole of C'B', AO is the axis of the great circle of which C'B' is an arc (?), hence is perpendicular to the plane C'OB', and consequently to OB' and OC' (?). In like manner, BO is perpendicular to the plane A'OC', and hence to OA' and OC'. So, also, CO is perpendicular to OA' and OB'. Now, these triedrals being supplementary, the diedral B-AO-C is the supplement of the facial angle C'OB' (*438*); or, since the diedral B-AO-C is the same as the spherical angle A, and the facial angle C'OB' is measured by a', A is the supplement of a', *i. e.*, $A = 180° - a'$. For like reasons, $B = 180° - b'$, and $C = 180° - c'$. [Let the student give them in full.] Again, the diedral B'-A'O-C' is the supplement of the facial angle COB (*438*); whence $A' = 180° - a$. In like manner $B' = 180° - b$, and $C' = 180° - c$.

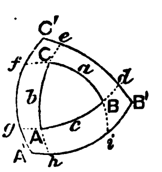

FIG. 344.

SECOND DEMONSTRATION.—Let ABC and A'B'C' be two polar triangles. Let CB, CA, and AB be represented by a, b, and c respectively, and C'B', C'A', and A'B' by a', b', and c'. To show that $A = 180° - a'$, produce b and c, if necessary, till they meet the side a', of the triangle polar to ABC, in e and d. Now A is measured by ed (*560*). But, since $C'd = 90°$, and $B'e = 90°$, $C'd + B'e$, or $C'B' + ed = 180°$; whence transposing, and putting a' for C'B', we have $ed = A = 180° - a'$. In like manner $C'g + A'f = C'A' + fg = 180°$; whence $fg = B = 180° - C'A'$, or $180° - b'$. So, also, $C = 180° - c'$. To show that $A' = 180° - a$, consider that A' being the pole of CB, fi is the measure of A'. Now $Bf = 90°$ (?), and $Ci = 90°$; whence $Bf + Ci = 180°$. But $Bf + Ci = fi + a$, wherefore $fi + a = 180°$, and transposing, and putting A' for fi, we have $A' = 180° - a$. In like manner we may show that $B' = 180° - b$, and $C' = 180° - c$. [The student should give the details.]

QUADRATURE OF THE SURFACE OF THE SPHERE.

596. The *Quadrature** of a surface is the same as finding its area. The term is applied under the conception that the process consists in finding a *square* which is equivalent to the given surface.

PROPOSITION XXV.

597. *Lemma.*—*The surface generated by the revolution of a regular semi-polygon of an even number of sides, about the diameter of the circumscribed circle as an axis, is equivalent to the circumference of the inscribed circle multiplied by the axis.*

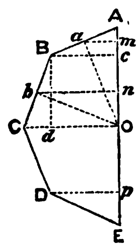

FIG. 345.

DEM.—Let ABCDE be one half of a regular octagon, AE being the diameter of the circumscribing circle. If the semi-perimeter ABCDE be revolved about AE as an axis, the surface generated will be $2\pi r \times \text{AE}$, r being the radius of the inscribed circle, as $a\text{O}$, or $b\text{O}$.

This surface is composed of the convex surfaces of cones and frustums of cones. Thus AB generates the surface of a cone, BC the frustum of a cone, etc. Let a and b be the middle points of AB and BC, and draw am, Bc, bn, and CO perpendicular to the axis, and Bd parallel to it. Also draw the radii of the inscribed circle, aO and bO. Indicate the surfaces generated by the sides, as *Surf.* AB, *Surf.* BC, etc. The areas of these surfaces are:

$$\textit{Surf.}\ \text{AB} = 2\pi \times am \times \text{AB}\ (\mathbf{516}), \qquad (1)$$
$$\textit{Surf.}\ \text{BC} = 2\pi \times bn \times \text{BC}\ (\mathbf{518}), \text{ etc.} \qquad (2)$$

Now, from the similar triangles Oam and BAc,

We have $a\text{O} : \text{AB} :: am : \text{A}c$, or $2\pi \times a\text{O} : \text{AB} :: 2\pi \times am : \text{A}c$;

Whence $2\pi \times am \times \text{AB} = 2\pi r \times \text{A}c$, putting r for aO.

Also, from the similar triangles Obn and CBd,

We have $b\text{O} : \text{BC} :: bn : \text{B}d\ (= c\text{O})$, or $2\pi \times b\text{O} : \text{BC} :: 2\pi \times bn : c\text{O}$;

Whence $2\pi \times bn \times \text{BC} = 2\pi r \times c\text{O}$, putting r for bO.

Substituting these values in (1) and (2), we obtain

$$\textit{Surf.}\ \text{AB} = 2\pi r \times \text{A}c,$$
$$\textit{Surf.}\ \text{BC} = 2\pi r \times c\text{O},$$

And, in like manner, $\textit{Surf.}\ \text{CD} = 2\pi r \times \text{O}p$,

And, $\textit{Surf.}\ \text{DE} = 2\pi r \times p\text{E}$.

Adding, $\textit{Surf.}\ \text{ABCDE} = 2\pi r\,(\text{A}c + c\text{O} + \text{O}p + p\text{E}) = 2\pi r \times \text{AE}$.

Finally, since the same course of reasoning is applicable to the semi-polygons of 16, 32, 64, etc., sides, the truth of the proposition is established.

---

* Latin *quadratus*, squared.

598. SCH.—This proposition is only a particular case of surfaces generated by *any* broken line revolving about an axis; and the general proposition can be established in a manner altogether similar to the method given above. But this case is all that we need for our present purpose.

PROPOSITION XXVI.

599. Theorem.—*The surface of a sphere is equivalent to four great circles; that is, to $4\pi R^2$, R being the radius of the sphere.*

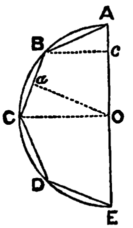

FIG. 346.

DEM.—Let the semicircumference ABCDE revolve upon the diameter AE, and thus generate the surface of a sphere. Conceive the half of a regular octagon inscribed in the semicircle. Call the radius of the inscribed circle, as aO, r, and let $AO = R$. The surface generated by the broken line ABCDE is, by the last proposition, $2\pi r \times 2R = 4\pi r R$. Now, conceive the arcs AB, BC, etc., bisected, and the chords drawn, and let r' be the radius of the circle inscribed in the regular polygon thus formed. The surface generated by this semi-polygon will be $4\pi r' R$. By repeating the bisections, the broken line approximates to the semicircumference, the radius of the inscribed circle to R, and the surface generated to the surface of the sphere, the three quantities reaching their limits at the same time. Hence *at* the limit we have

$$Surf. \text{ of sphere} = 2\pi R \times 2R = 4\pi R^2. \quad \text{Q. E. D.}$$

600. COR. 1.—*The area of the surface of a sphere is equivalent to the circumference of a great circle multiplied by the diameter, that is,* $2\pi R \times 2R$, *as above.*

601. COR. 2.—*The surfaces of spheres are to each other as the squares of their radii.*

Thus, if R and R′ are the radii of two spheres, the surfaces are $4\pi R^2$ and $4\pi R'^2$. Now, $4\pi R^2 : 4\pi R'^2 :: R^2 : R'^2$.

---

602. DEF.—***A Zone*** is the portion of the surface of a sphere included between the circumferences of two parallel circles of a sphere. The *altitude* of a zone is the distance between the parallel circles forming its bases.

ILL.—The surface generated by CB, or any arc of the circle ABCDE, *Fig.* 346, in its revolution, conforms to the definition, and is a zone. Such a portion of the surface as is generated by AB is called a zone with one base, the circle whose circumference would form the upper base having become tangent to the sphere.

PROPOSITION XXVII.

603. Theorem.—*The area of a zone is to the area of the surface of the sphere as the altitude of the zone is to the diameter of the sphere; which gives for the area of a zone* $2\pi aR$, a *being the altitude of the zone, and* R *the radius of the sphere.*

DEM.—It is evident that in passing to the limit the surface generated by such a portion of the broken line as would lie between C and B, *Fig.* 346, would be measured by the circumference of the inscribed circle multiplied by cO. Hence, at the limit, the zone generated by arc BC is measured by $2\pi R \times cO$, that is, it is such a part of the surface of the sphere as cO is of AE, or 2R. Letting a represent the altitude cO, the fraction $\frac{a}{2R}$ represents the part of the surface of the sphere constituting the area of the zone. Hence, $4\pi R^2 \times \frac{a}{2R}$, which equals $2\pi aR$, is the area of the zone.

604. COR.—*On the same or on equal spheres, zones are to each other as their altitudes.*

OF LUNES.

605. A Lune is a portion of the surface of a sphere included by two semicircumferences of great circles.

The surface $AmBn$ is a lune.

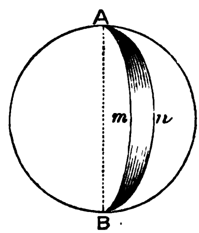

FIG. 347.

606. The *Angle of the Lune* is the angle included by the arcs which form its sides; or, what is the same thing, the measure of the diedral included between the great circles.

Thus, the spherical angle mAn, or the measure of the diedral m-AB-n, is the angle of the lune $AmBn$.

PROPOSITION XXVIII.

607. Theorem.—*The area of a lune is to the area of the surface of the sphere on which it is situated, as the angle of the lune is to four right angles.*

DEM.—Let ACEB be a lune whose angle is the spherical angle CAB, or what

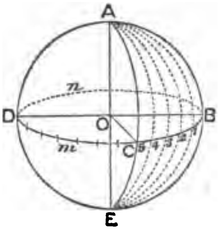

FIG. 348.

is the same thing, the plane angle BOC measured by the arc CB, of which A is the pole; then is

lune ACEB : *surface of sphere* :: CAB : 4 *right angles.*

For, suppose the arc CB commensurable with the circumference BCmDn, and suppose that they are to each other as 5 : 24. Dividing BC into 5 equal arcs, and the entire circumference BCmDn into 24 arcs of the same length, and passing arcs of great circles through A and these points of division, the lune will be divided into 5 equal lunes, and the entire surface into 24 equal lunes of the same size. That these lunes are equal to each other is evident from the fact that they are composed of equal isosceles triangles. Hence,

lune ACEB : *surface of sphere* : : 5 : 24.

Now, *angle* BOC : 4 *right angles* :: BC (= 5) : BCmDn (= 24).

Therefore, *lune* ACEB : *surface of sphere* :: BOC (or CAB) : 4 *right angles*,

since the circumference measures 4 right angles.

If BC has no finite common measure with the circumference, we may divide it into any number of equal arcs, bisect these arcs, then bisect the last formed, and continue the process of bisection (in conception) to any required extent; and as, when any one of the arcs thus obtained is applied to the circumference, if it is not an exact measure, the remainder is less than the arc, we can continue the subdivision of BC (in conception) until this remainder is less than any assignable quantity. Hence, we may always consider the arc BC as commensurable with the circumference by making the measure infinitesimal.

608. COR.—*The sum of several lunes on the same sphere is equal to a lune whose angle is the sum of the angles of the lunes; and the difference of two lunes is a lune whose angle is the difference of their angles.*

609. SCH. 1.—The case in which the arc measuring the angle of the lune is incommensurable with the circumference, may be treated as in (***206***), by the method of reasoning called the *Reductio ad absurdum*, *i. e.*, by showing a thing to be true, since it would be absurd to suppose it untrue.

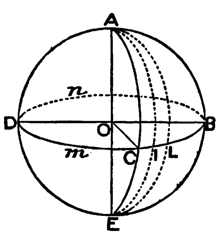

FIG. 349.

Thus, there is some arc to which the circumference bears the same ratio as the surface of the sphere does to the surface of the lune. If that arc be not BC let it be BL, an arc *less* than BC, so that

surface of sphere : *lune* ACEB : : BCmDn : BL. (1)

Conceive the circumference BCmDn divided into equal parts, each of which is less than CL, the assumed difference between BC and BL. Then conceive one of these equal parts applied to BC as a measure, beginning at B. Since the measure is less

than LC, one point of division, at least, will fall between L and C. Let I be such a point, and pass the arc of a great circle through A and I.

Now, *surface of sphere* : *lune* AIEB : : BCmDn : BI, (2)

since the arc BI is commensurable with the circumference. In (1) and (2), the antecedents being equal, the consequents should be proportional, hence we should have

lune ACEB : *lune* AIEB : : BL : BI.

But this is absurd, since *lune* ACEB > lune AIEB, whereas BL < BI. In a similar manner we can show that

surface of sphere is not to *lune* ACEB : : BCmDn : any arc greater than BC.

Hence, as the fourth term can neither be less nor greater than BC, it must be equal to BC, and we have

surface of sphere : *lune* ACEB :: BCmDn : BC,

i. e., as 4 right angles, to the angle of the lune.

610. Sch. 2.—*To obtain the area of a lune whose angle is known, on a given sphere*, find the area of the sphere, and multiply it by the ratio of the angle of the lune (in degrees) to 360°. Thus, R being the radius of the sphere, $4\pi R^2$ is the surface of the sphere; and the lune whose angle is 30° is $\frac{30}{360}$ or $\frac{1}{12}$ the surface of the sphere, *i. e.*, $\frac{1}{12}$ of $4\pi R^2 = \frac{1}{3}\pi R^2$.

PROPOSITION XXIX.

611. Theorem.—*If two semicircumferences of great circles intersect on the surface of a hemisphere, the sum of the two opposite triangles thus formed is equivalent to a lune whose angle is that included by the semicircumferences.*

Dem.—Let the semicircumferences CEB and DEA intersect at E on the surface of the hemisphere whose base is CABD; then the sum of the triangles CED and AEB is equivalent to a lune whose angle is AEB.

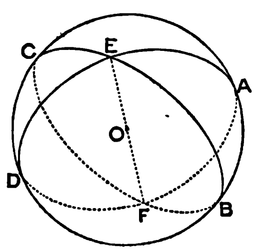

Fig. 350.

For, let the semicircumferences CEB and DEA be produced around the sphere, intersecting on the opposite hemisphere, at the extremity F of the diameter through E. Now, FBEA is a lune whose angle is AEB. Moreover, the triangle AFB is equivalent to the triangle DEC: since angle AFB = AEB = DEC, side AF = side ED, each being the supplement of AE; and BF = CE, each being the supplement of EB. Hence, the sum of the triangles CED and AEB is equivalent to the lune FBEA. Q. E. D.

PROPOSITION XXX.

612. Theorem.—*The area of a spherical triangle is to the area of the surface of the hemisphere in which it is situated, as its spherical excess is to four right angles, or* 360°.

DEM.—Let ABC be a spherical triangle whose angles are represented by A, B, and C; then is

area ABC : *surf. of hemisphere* : : A + B + C − 180° : 4 *right angles*, or 360°.

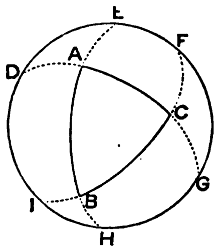

FIG. 351.

Let *lune* A represent the lune whose angle is the angle A of the triangle, *i. e.*, angle CAB, and in like manner understand *lune* B and *lune* C.

Now, triangle AHG + AED = *lune* A (**611**),

BHI + BEF = *lune* B,

CGF + CDI = *lune* C.

Adding, 2ABC + *hemisphere* = *lune* (A + B + C)*, (1) since the six triangles AHG, AED, BHI, BEF, CGF, and CDI, make the whole hemisphere and 2ABC besides, ABC being reckoned *three* times. From (1), we have by transposing and remembering that a hemisphere is a lune whose angle is 180°, and dividing by 2,

$$ABC = \tfrac{1}{2}\,lune\,(A + B + C - 180°).$$

But, by (**607**),

$\frac{1}{2}$ *lune* (A + B + C − 180°) : *surf. of hemisph.* : : A + B + C − 180° : 4 *right angles.*

Therefore, ABC : *surf. of hemisph.* : : A + B + C − 180° : 4 *right angles.*

613. SCH. 1.—*To find the area of a spherical triangle* on a given sphere, the angles of the triangle being given, we have simply to multiply the area of the hemisphere, *i. e.*, $2\pi R^2$, by the ratio of the spherical excess to 360°. Thus, if the angles are A = 110°, B = 80°, and C = 50°, we have

$$area\ ABC = 2\pi R^2 \times \frac{A + B + C - 180°}{360°} = 2\pi R^2 \times \frac{60}{360} = \tfrac{1}{3}\pi R^2.$$

614. SCH. 2.—This proposition is usually stated thus: *The area of a spherical triangle is equal to its spherical excess multiplied by the trirectangular triangle.* When so stated the spherical excess is to be estimated in terms of the right angle; *i. e.*, having subtracted 180° from the sum of its angles, we are to divide the remainder by 90°, thus getting the spherical excess in right angles. In the example in the preceding scholium, the spherical excess estimated in this way would be $\frac{110° + 80° + 50° - 180°}{90°} = \frac{2}{3}$; and the area of the triangle would

* This signifies the lune whose angle is A + B + C, which is of course the sum of the three lunes whose angles are A, B, and C.

be $\frac{2}{3}$ of the trirectangular triangle. Now, the trirectangular triangle being $\frac{1}{8}$ of the surface of the sphere (*577*) is $\frac{1}{8}$ of $4\pi R^2$, or $\frac{1}{2}\pi R^2$. This multiplied by $\frac{2}{3}$ gives $\frac{1}{3}\pi R^2$, the same as above.

The proportion,

$$\text{ABC} : \textit{surf. of hemisph.} :: \text{A} + \text{B} + \text{C} - 180° : 360°,$$

is readily put into a form which agrees with the enunciation as given in this scholium. Thus, *surf. of hemisph.* $= 2\pi R^2$, whence

$$\text{ABC} = 2\pi R^2 \times \frac{\text{A}+\text{B}+\text{C}-180°}{360°} = \tfrac{1}{2}\pi R^2 \times \frac{\text{A}+\text{B}+\text{C}-180°}{90°}.$$

VOLUME OF SPHERE.

PROPOSITION XXXI.

615. Theorem.*—The volume of a sphere is equal to the area of its surface multiplied by $\frac{1}{3}$ of the radius, that is, $\frac{4}{3}\pi R^3$, R being the radius.*

DEM.—Let $\text{OL} = \text{R}$ be the radius of a sphere. Conceive a circumscribed cube, that is, a cube whose faces are tangent planes to the sphere. Draw lines from the vertices of each of the polyedral angles of the cube, to the centre of the sphere, as BO, CO, DO, AO, etc. These lines are the edges of six pyramids, having for their bases the faces of the cube, and for a common altitude the radius of the sphere (?). Hence the volume of the circumscribed cube is equal to its surface multiplied by $\frac{1}{3}$R.

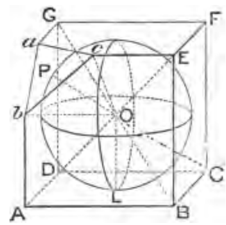

FIG. 352.

Again, conceive each of the polyedral angles of the cube truncated by planes *tangent to the sphere.* A new circumscribed solid will thus be formed, whose volume will be nearer that of the sphere than is that of the circumscribed cube. Let *abc* represent one of these tangent planes. Draw from the polyedral angles of this new solid, lines to the centre of the sphere, as *a*O, *b*O, and *c*O, etc.; these lines will form the edges of a set of pyramids whose bases constitute the surface of the solid, and whose common altitude is the radius of the sphere (?). Hence the volume of this solid is equal to the product of its surface (the sum of the bases of the pyramids) into $\frac{1}{3}$R.

Now, this process of truncating the angles by tangent planes may be conceived as continued indefinitely; and, to whatever extent it is carried, it will *always* be true that the volume of the solid is equal to its surface multiplied by $\frac{1}{3}$R. Therefore, as the sphere is the limit of this circumscribed solid, we have the volume of the sphere equal to the surface of the sphere, which is $4\pi R^2$, multiplied by $\frac{1}{3}$R, *i. e.*, to $\frac{4}{3}\pi R^3$. Q. E. D.

616. COR.—*The surface of the sphere may be conceived as consisting of an infinite number of infinitely small plane faces, and the volume as composed of an infinite number of pyramids having these faces for their bases, and their vertices at the centre of the sphere, the common altitude of the pyramids being the radius of the sphere.*

617. ***A Spherical Sector*** is a portion of a sphere generated by the revolution of a circular sector about the diameter around which the semicircle which generates the sphere is conceived to revolve. It has a zone for its base; and it may have as its other surfaces one, or two, conical surfaces, or one conical and one plane surface.

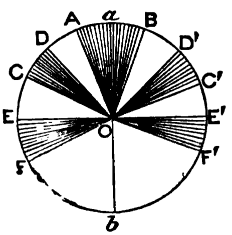

FIG. 353.

ILL.—Thus let ab be the diameter around which the semicircle aCb revolves to generate the sphere. The solid generated by the circular sector AOa will be a spherical sector having a zone (AB) for its base; and for its other surface, the conical surface generated by AO. The spherical sector generated by COD, has the zone generated by CD for its base; and for its other surfaces, the concave conical surface generated by DO, and the convex conical surface generated by CO. The spherical sector generated by EOF, has the zone generated by EF for its base, the plane generated by EO for one surface, and the concave conical surface generated by FO for the other.

618. ***A Spherical Segment*** is a portion of the sphere included by two parallel planes, it being understood that one of the planes may become a tangent plane. In the latter case, the segment has but one base; in other cases, it has two. A spherical segment is bounded by a zone and one, or two, plane surfaces.

PROPOSITION XXXII.

619. ***Theorem.***—*The volume of a spherical sector is equal to the product of the zone which forms its base into one-third the radius of the sphere.*

DEM.—A spherical sector, like the sphere itself, may be conceived as consisting of an infinite number of pyramids whose bases make up its surface, and whose common altitude is the radius of the sphere. Hence, the volume of the sector is equal to the sum of the bases of these pyramids, that is, the surface of the sector, multiplied by one-third their common altitude, which is one-third the radius of the sphere. Q. E. D.

620. COR.—*The volumes of spherical sectors of the same or equal spheres are to each other as the zones which form their bases; and, since these zones are to each other as their altitudes* (**604**), *the sectors are to each other as the altitudes of the zones which form their bases.*

PROPOSITION XXXIII.

621. Theorem.—*The volume of a spherical segment of one base is* $\pi A^2(R - \frac{1}{3}A)$, A *being the altitude of the segment, and* R *the radius of the sphere.*

DEM.—Let $CO = R$, and $CD = A$; then is the volume of the spherical segment generated by the revolution of CAD about CO equal to $\pi A^2(R - \frac{1}{3}A)$.

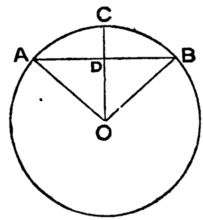

FIG. 354.

For, the volume of the spherical sector generated by AOC is the zone generated by AC, multiplied by $\frac{1}{3}R$, or $2\pi AR \times \frac{1}{3}R = \frac{2}{3}\pi AR^2$. From this we must subtract the cone, the radius of whose base is AD, and whose altitude is DO. To obtain this, we have $DO = R - A$: whence, from the right angled triangle ADO, $AD = \sqrt{R^2 - (R - A)^2} = \sqrt{2AR - A^2}$. Now, the volume of this cone is

$$\tfrac{1}{3}OD \times \pi \overline{AD}^2, \text{ or } \tfrac{1}{3}\pi(R - A)(2AR - A^2) = \tfrac{1}{3}\pi(2AR^2 - 3A^2R + A^3).$$

Subtracting this from the volume of the spherical sector, we have

$$\tfrac{2}{3}\pi AR^2 - \tfrac{1}{3}\pi(2AR^2 - 3A^2R + A^3) = \pi(A^2R - \tfrac{1}{3}A^3) = \pi A^2(R - \tfrac{1}{3}A). \quad \text{Q. E. D.}$$

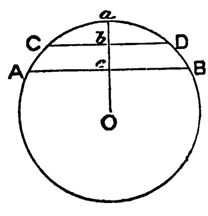

FIG. 355.

622. SCH.—The volume of a spherical segment with two bases is readily obtained by taking the difference between two segments of one base each. Thus, to obtain the volumes of the segment generated by the revolution of *b*CA*c* about *a*O, take the difference of the segments whose altitudes are *ac* and *ab*.

EXERCISES.

1. What is the circumference of a small circle of a sphere whose diameter is 10, the circle being at 3 from the centre?

Ans., 25.1328.

2. Construct on the spherical blackboard a spherical angle of 60°. Of 45°. Of 90°. Of 120°. Of 250°.

SUG'S.—Let P be the point where the vertex of the required angle is to b situated. With a quadrant strike an arc from P, which shall represent one side of the required angle. From P as a pole, with a quadrant, strike an arc from the side before drawn, which shall measure the required angle. On this last arc lay off from the first side the measure of the required angle,* as 60°, 45°, etc. Through the extremity of this arc and P pass a great circle (*548*). [The student should not fail to give the reasons, as well as *do* the work.]

3. On the spherical blackboard construct a spherical triangle ABC, having $AB = 100°$, $AC = 80°$, and $A = 58°$.

4. Construct as above a spherical triangle ABC, having $AB = 75°$, $A = 110°$, and $B = 87°$.

5. Construct as above, having $AB = 150°$, $BC = 80°$, and $AC = 100°$. Also having $AB = 160°$, $AC = 50°$, and $BC = 85°$.

6. Construct as above, having $A = 52°$, $AC = 47°$, and $CB = 40°$.

SUG'S.—Construct the angle A as before taught, and lay off AC from A equal to 47°, with the tape. This determines the vertex C. From C, as a pole, with an arc of 40°, describe an arc of a small circle; in this case this arc will cut the opposite side of the angle A in two places. Call these points B and B'. Pass circumferences of great circles through C, and B, and B'. There are two triangles, ACB and ACB'.

NOTE.—The teacher can multiply examples like the three preceding at pleasure. This exercise should be continued till the pupil can draw a spherical triangle as readily as a plane triangle.

7. What is the area of a spherical triangle on the surface of a sphere whose radius is 10, the angles of the triangle being 85°, 120°, and 150°? *Ans.*, 305.4 +.

8. What is the area of a spherical triangle on a sphere whose diameter is 12, the angles of the triangle being 82°, 98°, and 100°?

9. A sphere is cut by 5 parallel planes at 7 from each other. What are the relative areas of the zones? What of the segments?

10. Considering the earth as a sphere, its radius would be 3958 miles, and the altitudes of the zones, North torrid = 1578, North temperate = 2052, and North frigid = 328 miles. What are the relative areas of the several zones?

SUG.—The student should be careful to discriminate between the *width* of a zone, and its altitude. The altitudes are found from their widths, as usually given in degrees, by means of trigonometry.

---

* For this purpose a tape equal in length to a semicircumference of a great circle of the sphere used, and marked off into 180 equal parts, will be convenient. A strip of paper may be used.

11. The earth being regarded as a sphere whose radius is 3958 miles, what is the area of a spherical triangle on its surface, the angles being 120°, 130°, and 150°? What is the area of a trirectangular triangle on the earth's surface?

12. Construct on the spherical blackboard a spherical triangle ABC, having $A = 59°$, $AC = 120°$, and $AB = 88°$. Then construct the triangle polar to ABC.

13. Construct triangles polar to each of those in Examples 3, 4, and 5.

14. In the spherical triangle ABC given $A = 58°$, $B = 67°$, and $AC = 81°$; what can you affirm of the polar triangle?

15. What is the volume of a globe which is 2 feet in diameter? What of a segment of the same globe included by two parallel planes, one at 3 and the other at 9 inches from the centre?

16. Compare the convex surfaces of a sphere and its circumscribed cylinder and cone, the vertical angle of the cone being 60°.

17. Compare the volumes of a sphere and its circumscribed cube, cylinder, and cone, the vertical angle of the cone being 60°.

18. If a and b represent the distances from the centre of a sphere whose radius is r, to the bases of a spherical segment, show that the volume of the segment is $\pi[r^2(b - a) - \frac{1}{3}(b^3 - a^3)]$. See (*621*, *622*).

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